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Demand-Side Management in Office Buildings in Kuwait through an Ice-Storage Assisted HVAC System with Model Predictive Control

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ABSTRACT

Examining methods for controlling the electricity demand in Kuwait was the main objective and motivation of this research project. The extensive use of air-conditioning for indoor cooling in office and large commercial buildings in Kuwait and the Gulf States represents a major part of the power and electricity consumption in such countries. The rising electricity generation cost and growing rates of consumption continuously demand the construction new power plants. Devising and enforcing Demand-Side Management (DSM) in the form of energy efficient operation strategies was the response of this research project to provide a means to rectify this situation using the demand-side management technique known as demand levelling or load shifting. State of the art demand-side management techniques have been examined through the development of a model based predictive control optimisation strategy for an integrated and modular approach to the provision of ice thermal storage.

To evaluate the potential of ice-storage assisted air-conditioning systems in flattening the demand curve at peak times during the summer months in Kuwait, a model of a Heating, Ventilation, and Air-conditioning (HVAC) plant was developed in Matlab. The model engaged the use of model based predictive control (MPC) as an optimisation tool for the plant as a whole. The model with MPC was developed to chose and decide on which control strategy to operate the integrated ice-storage HVAC plant. The model succeeded in optimising the operation of the plant and introduced encouraging improvement of the performance of the system as a whole.

The concept of the modular ice-storage system was introduced through a control zoning strategy based on zonal orientation. It is believed that such strategy could lead to the modularisation of ice-storage systems. Additionally, the model was examined and tested in relation to load flattening and demonstrated promising enhancement in the shape of the load curve and demonstrated flattened demand curves through the employed strategy. When compared with measured data from existing buildings, the model showed potential for the techniques utilised to improve the load factor for office buildings.

Keywords:

Demand-Side Management, Load Shifting, Air-Conditioning, HVAC, Buildings, Thermal Energy Storage, Ice-Storage, Office Buildings, Power Consumption, Model Predictive Control, Energy Efficient Operation Strategies, Energy Efficient Control Strategies, Load Shifting, Demand Curve Flattening, Peak Power Demand, Kuwait.

بسم الله الرحمن الرحيم

All gratefulness and praises be to Allah, the god of Adam, Abraham, Moses, Jesus and Mohammad. Peace be upon them all.

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DEDICATION

TO

MY MOTHER

&

MY WIFE

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"We shape our buildings and, in turn, our buildings shape us." - Sir Winston Churchill.

Chapter 1

Introduction

1.1 Reasons behind this Thesis

With a world of growing demand for energy and power, a balance between electricity supply and demand has become a vital requirement in order to conserve the capabilities to provide for the high levels of standards of living that nations expect. In addition, to be able to reach a nation's environmental protection goals, such a balance must be given the highest priority in order to preserve the natural resources of the earth and to ensure protection to the local and global environments.

The uncertainty in future demand, fuel prices and availability and the increase in the cost of power generation and distribution in addition to crucial environmental issues are of great concern to governments and utilities. Motivated by the rising electricity generation cost, which is represented by the growing consumption and the need for constructing new power plants; the need for devising and enforcing *Demand Side Management* (DSM) plans in the form of energy efficient operation strategies to curtail the excessive consumption of energy in air-conditioned buildings has been established. Examining methods for controlling the electricity demand in Kuwait is the main objective of this research work. This is by means of employing state of the art DSM techniques.

This thesis aims to utilise a *Demand Side Management* (DSM) strategy towards reducing the electricity consumption in commercial and office buildings in Kuwait. This can be achieved through identifying demand control methods of the electricity supplied to those buildings. The reason behind this is because of the continuously growing demand that Kuwait has and continues to experience.

Thermal Energy Storage (TES), in the form of ice storage system, is the basis of this investigation. Thermal (cooling) energy storage is accounted as a load shifting strategy because it involves shifting the cooling load from the peak of consumption to other periods (off-peak) where consumption rates are considerably less. In the case of ice-storage systems, the storage system is charged by producing ice during these off-peak periods and then to use that ice to cool the building during peak consumption periods, thus shifting the electricity load.

As the scope and objective of this research work is to introduce a DSM strategy through the optimisation of an ice thermal storage model with an integrated model of a predictive control strategy, load shifting has become the key measure to be investigated. The objective is to achieve this through the use of an intelligent device, *Model Predictive Control* (MPV), which will respond to predicted patterns of demand and work to optimise the ice charging and discharging process.

1.2 The Aim of the Thesis

This thesis aims to utilise a DSM strategy towards reducing the electricity consumption in commercial and office buildings in Kuwait. This is through the establishment of a MPC strategy for the optimisation of ice-storage assisted air-conditioning systems adopted in such buildings. MPC is the optimisation tool that will allow the testing and examination of different operation modes of building services in office buildings. MPC will be utilised to arrive at the optimum operating conditions of ice-storage assisted air-conditioning systems through the iterative filtering process that it uses.

1.3 Overview of the Thesis

The MPC model introduced in this work is capable of providing prediction of the optimum operation strategy for the system. Yet, an addition is recommended for the model to evaluate the predicted status of the ice-storage, and then provide comparison between the amount of stored energy and the amount consumed. Then to judge the exact amount of energy that should be stored and limit the needed energy to be stored to that quantity.

Chapter 2. Demand Side Management and its Integrated Strategies

This chapter reviews some of the literature available regarding Demand Side Management (DSM). A general coverage of the concept and definition are included. The aim is to provide a link between DSM and air-conditioning systems in office buildings. A revision of DSM objectives is also covered. The relationship between DSM and load management is considered. Exploration of the influence of DSM programmes on the shape of demand curves is also highlighted. Finally, the potential benefits of DSM are also explored.

Chapter 3. The Electricity Supply Industry in Kuwait

In order to fully comprehend the aims and objectives of this research work, it is necessary describe the characteristics of the electricity supply industry in Kuwait. This chapter reflects upon the reasons that originated the objectives of this research work by focussing on the problem that arise regarding energy consumption and power generation in Kuwait due to the use of air-conditioning systems.

An overview of the electricity supply industry in Kuwait is given. An examination of the climate characteristics in Kuwait is presented. In addition, economic growth patterns and the change in the composition of the built environment are investigated. Initial application of DSM through energy conservation measures, energy auditing towards reducing the consumption of electricity and other energy efficiency measure are listed through some examples related to the Kuwaiti context.

Chapter 4. Ice Thermal Storage as a Demand Side Management Strategy
This chapter aims to introduce an overall presentation of ice thermal storage, its basic concepts in brief and the strategies that can be associated with it. A review on thermal storage systems, their types and the relative merits of the different storage media is included. Furthermore, a review of ice-storage systems operation strategies and operation strategies are incorporated.

Chapter 5. Examination of Demand Side Management through Zoning and Plant Modularisation – The Building and HVAC Models
This chapter aimed at examining the effect of zoning on a building cooling demand. A review of buildings and their stereotypes was undertaken. This provided the base for the development of the stereotypes for modelling, as the main two types of buildings stereotypes most commonly found in Kuwait. This chapter demonstrated that the most common forms of modern office buildings found in Kuwait represent either the "deep plan" or "long thin" stereotypes. Consequently, to satisfy the objective of this work, these two forms of building plan have been chosen for investigation. The selected two types of layout were used to ascertain the load profiles in relation to orientation and to consider how these might affect the development of building environmental services control zoning and the development of strategies for integrated ice storage systems in office buildings in Kuwait.

Thermal Analysis Software (TAS) was the tool used to build the dynamic thermal models of the two forms of office building stereotypes. The models represent modern types of office building with thermally lightweight structures. Kuwaiti weather data was set up in the modelling process and this allowed the dynamic thermal behaviour of the building models in relation to the Kuwaiti environment to be investigated. The main purpose for using TAS was to study the dynamic behaviour of the stereotypical office building models developed. TAS allowed a preliminary in-depth study of the likely load profiles for typical office buildings. In addition, examination of the effect of orientation on the building load was examined.

However, for the purpose of the main elements of the research work, the decision was made to use Matlab software with its capabilities so as to provide a good basis to examine the feasibility of the proposed system. Consequently, Matlab was considered to provide the ability to develop models to predict the thermal behaviours of building zones that are in turn linked to models of the components of building services systems and their associated controls. This gives a broader base for studying all the subsystems under the umbrella of a one complete model.

Chapter 6. The Ice-Storage Model with Model Predictive Control
The task in this chapter was to report on the modelling of the ice-storage system type selected for this research work. An indirect, ice-on-coil, system is the type of system chosen to be modelled and studied through the core of this chapter. The literature review presented in the previous chapter had highlighted this as the most appropriate system. As the aim is to incorporate a model predictive control (MPC) strategy to assure optimum operation of the system as whole, the subjects of both system identification and MPC are first introduced. Also, some of the different approaches applied by others have been considered in this chapter. This is to reflect the difference between the theoretical development of ice-storage models and the black box approach utilised as the methodology of modelling for this research work. Finally, the chapter covers the modelling methodology adopted to build the system with the chiller, ice-storage and cooling coil components. A flow diagram of the model predictive control strategy is presented.

Chapter 7. A Model Predictive Control Strategy for an Ice-Storage Assisted HVAC System
Examining the model predictive control strategy (MPC) of the chosen configuration that is thought to be most suitable for application in a country like Kuwait is conducted in this chapter. For the purpose of the new strategy, the simulink building model with AHU, Chapter 5, is linked to a matlab algorithm that represents the same system with the addition of the chiller and ice-storage unit. The role of the MPC is to update the system on an hourly basis and ascertain how best it will behave related to the newly measured values of the- introduced variables. The initial simulink model did not have a chiller component included. In this chapter, the effect of the different zones was also emphasized. The initial simulink building zone model was used to provide the load variations that acted as a base for the model predictive control strategy implemented. This base model is capable of showing the dependence of the cooling load on the different variables such as weather conditions, machines, lighting, occupancy and non-occupancy periods.

Two different operation strategies that utilise different indoor temperatures are tested. Results were demonstrated to show that the developed model is capable of dealing with the dynamic variation in the parameters involved. Following, a deeper examination of the results was undertaken. The behaviours of the different zones for both the constant set zone temperature and the variable set zone temperature strategies were investigated.

The model was also tested against its effect on the load curve and the load factor.

Chapter 8. Conclusions and Future Work
This chapter considers what this research work has demonstrated and summarises the key stages of the work. As mentioned in Chapter 7, the model was able to modify its behaviour with the change in the nature of the demand. The model was able to shift between a cooling and charging strategy, and a cooling and discharging strategy. Although the model was able to predict the next day load; yet, proper constraints need

to be added to the model to better control the charging process so that it becomes limited to only the provide the ice-storage needs required for the future predicted time horizon.

"Energy and environment are essential for sustainable development. Tailored strategies for sustainable development are country-based and country-owned systems providing a coordinated set of participatory and continually improving component processes, at national and local levels. A strategy must evolve into an iterative learning system to develop a shared vision and make progress towards sustainable development" ... United Nations Development Programme, UNDP

Chapter 2

Demand-Side Management & its Integrated Strategies

2.1 Introduction

This thesis aims to utilise a *Demand Side Management* (DSM) strategy towards reducing the electricity consumption in commercial and office buildings in Kuwait. This can be achieved through identifying demand control methods of the electricity supplied to those buildings. *Supply Side Management* (SSM) was and still is the elected option for the provision of electricity demand in Kuwait. As will be highlighted in chapter 3, Kuwait has and continues to experience a growing demand for electricity. The Ministry of Electricity and Water (MEW), the only power supplier in Kuwait, relies upon the construction of new power plants to cope with this ever increasing demand. In the past it was perceived that few threats to natural resource of oil in Kuwait existed and so supply side management was considered to be an acceptable option. In addition, SSM was convenient at a time when concerns related to the potential of fossil fuel combustion to change the earth's climate were minimal and the notion of sustainable development was just appearing.

Energy shortage, environmental degradation and the rapid growth in the cost of electrical power production and the energy industries in Kuwait have forced a major shift from SSM towards the development of DSM. This not only provided possibilities to meet the growth in the demand of power and energy by reducing consumption rates, yet it provided the opportunities for optimising energy efficiency through improved operation and control strategies in buildings and integrated building services systems.

High levels of energy efficiency can not be achieved only through the design and construction of energy-efficient buildings and modern building services. Energy savings, in addition to reduction in cost, can only be achieved if a building and its systems are used for the purpose for which they are designed. Equally important, is the introduction and development of DSM operation strategies that target energy efficiency and cost performance. This ensures that initial savings in capital cost are reflected in ongoing savings in energy consumption and consequently the running costs of a building with its systems.

The term 'demand-side management' (DSM) was first used in the United States in the early 1980s. The term was used to describe the planning and implementation of electricity utilisation strategies that were designed to influence the time, pattern and/or amount of electricity demand by customers to produce desired changes in the shape of the utility's demand load and to increase customer satisfaction. DSM was considered to provide an alternative to growth in the capacity of the electricity generation system as well as a tangible means of providing customers with a valuable service. The United Kingdom, Europe, and Australia quickly followed in the adoption of DSM and currently DSM-associated initiatives are practised worldwide. The DSM strategies promoted by energy companies aimed to reduce both energy consumption rates and peak loads that the energy supplier had to provide for. The key objective of DSM for the energy companies was to try to minimise the cost of electricity production by determining which electricity capacity solution was the more cost effective: adding generation capacity or reducing electricity use. If a future shortage of electricity generation capacity was foreseen, a choice existed either to build new power plant or in to invest in energy efficiency on the part of major energy users. Electricity demand growth problems can be solved either through the more efficient use of electrical energy, e.g. in industrial plant or by utilising more energy efficient air conditioning for homes and offices, or by building new power plants and other infrastructure. The adoption of a strategy to make more efficient use of the energy utility has the advantage in that it also contributes to a reduction in CO_2 generation and saves costs for society as a whole and as individual customers.

Energy efficiency measures as part of a DSM strategy can lead to savings of up to 20% in energy costs. This may be through the utilisation of energy efficient lighting, energy efficient glazing for windows, proper computation methods that allow the calculation of a building load more accurately, in addition to many other measures. A key aspect of DSM is the utilisation of proper control of building services system, such as HVAC systems. Technologies exist in the form of programmable thermostats that allow the programming of several schedules for running an HVAC system at different modes. Energy recovery units are another form that helps achieve reduction in energy consumption. Advancement in science and technology does not stop at that level. At present, the introduction of advanced computing and control methods may improve efficiency and allow much higher savings in the capital cost and running cost of such systems. Techniques range from *Building Energy Management Systems* (BEMS), some times known as *Building Automation Systems* (BAS), that allow the monitoring and control of systems more closely, to intelligent controllers that adopt algorithms such as *Artificial Neural Networks* (ANN), *Fuzzy Logic* (FL), in addition to systems such as *Model Predictive Control* (MPC) that usually aims at predicting the optimum operation conditions for future demand patterns of a real plant . Such intelligent techniques allow the introduction of DSM in an improved form through the control of power demand through demand based response techniques.

At an early stage of this research project, the broad aim was to study the development of energy efficient operation strategies for air-conditioning systems in office buildings. However, the key objective was the development of a model based predictive control strategy for an integrated and modular approach to the provision of ice thermal storage. A demand-response based approach was to be examined through the utilisation of predictive control of an ice storage system.

This chapter aims to provide an introduction of the concepts involved in demand-side management and some of its integrated strategies.

2.2 Demand Side Management

With a world of growing demand for energy and power, a balance between electricity supply and demand has become a vital requirement in order to conserve the capabilities to provide for the high levels of standards of living that nations expect. In addition to being able to reach a nation's environmental protection goals, such balance must be given the highest priority in order to preserve the natural resources of the earth and to ensure protection to the environment.

It is important to highlight that no standard definition for DSM exists. Many references define DSM from the perspective of their own interest or point of view. This can be acceptable to some degree. The basics notions of the DSM concept might apply to a global level; however, going into a more specific environment then the specific framework of a DSM strategy should be tailored to suit that specific environment. The Electrical Power Research Institute (EPRI 1984) defines DSM as: *"The planning, implementation and monitoring of utility activities designed to influence customer use of electricity in ways that will produce desired changes in load shape – i.e., in the time pattern and magnitude of a utility's load. Utility programs falling under the umbrella of demand-side management include load management, new uses, strategic conservation, electrification, customer generation, and adjustment in market share"*. In his review of the different definitions of DSM, Williamson (1996) states that, there seemed to be a degree of confusion as to what the term demand-side management meant. In a review of more than 70 integrated resources planning projects Chamberlin reported that not a single one agreed with the above EPRI definition, (in EPRI (1993)). Instead, DSM has been used to loosely define measures involving improved efficiency, load management and conservation, emphasising the reduction in electrical energy use and/or generation capacity. Other terms include Integrated Resource Planning (IRP) and Least-Cost Planning (LCP).

Williamson (1996) refers to definitions from the UK; the energy saving trust used the following definition *"DSM is the application of energy efficiency measures where the electricity network is under stress in order to defer/prevent expenditure on network reinforcement"*. In a report prepared for the Office of Electricity Regulation (OFFER), by LE Energy Ltd and SRC International Aps, 1992; DSM is defined as *"Measures* *taken by an electricity supplier or other party, apart from the electricity consumer, to reduce a consumer's demand for electricity through improving in the efficiency with which electricity is used"; "The implementation of DSM will usually involve the expenditure of capital in the customer's premises to improve efficiency of use, with recovery of the expenditure through savings in the cost of supplying electricity and through increased electricity prices ... DSM also includes measures to reduce electricity costs by transferring demand from periods of higher electricity pricesto periods when prices are lower,* or to times of lower demand, *these latter measures may or may not involve an overall change in overall consumption".*

Another UK author, Deobie (1993) states: *"Demand-Side Management (DSM) is defined as the planning, implementation and monitoring of utility activities, aimed at modifying customer end-use energy utilisation to give least cost combination of investment in energy supply infrastructure and energy efficiency programmes to provide customers with a better service at lower cost",* from Williamson (1996).

Gellings (1993), asserts that *"DSM is a set of activities which involves action on the demand (customer) side of the power meter and which is initiated by the utility. Such activities include load management, conservation, electrification and strategic growth of market share".*

Many of the definitions and statements tend to consider demand-side management as a tool that can be utilised mainly by energy generators and suppliers, with more interest from the suppliers. However, that probably is not totally true. A view more dominant in European practice and one that is accepted by the International Energy Agency Demand-Side Management Programme (IEA-DSM) Implementing Agreement is that the term "Demand Side" applies equally to all types of energy sources and activities on the demand side and can be undertaken by many actors, not only the suppliers. DSM can be looked upon either- as a tool to be used to change the demand for energy or, more generally, as a tool for society to better use and distribute scarce resources. In both cases, at least as far as this agreement is concerned, the main thrust and reasons for DSM activities are due to the necessity to increase energy efficiency and receive better value for the capital invested in the energy system, IEA-DSM (DSMspotlight March 2001).

It is most likely that such implementation would be more acceptable on international basis. A demand-side management plan or strategy initiated in one specific environment would carry the possibility that it can be adopted in another different environment. Beggs (2002), argues this issue by referring to the case of UK. He states, that because of the complex nature of the UK's horizontally integrated electricity supply industry, the role of DSM in the UK is somewhat ambiguous. He suggests that in theory all parties in the UK electricity supply industry benefit from the introduction of DSM. However, because of the fragmentations of the industry due to horizontal integration he considers that it is difficult to initiate and coordinate an effective DSM policy. For example, he asks who will pay for a DSM policy? Are the regional distribution companies going to pay for a policy which arguably gives greatest benefits to the generators and the National Grid Company (NGC)? It is also difficult for the competing generators to initiate DSM, since they have no 'captive' market and they have little direct influence over the end users. The structure of the electricity market in the UK is such that individual generators are always seeking to generate as much electricity as possible. The benefit to the generators through the implementation of a DSM policy is dubious - since there is over capacity in the system and every generator benefits from higher electricity prices when demand is high. Therefore, for DSM to succeed in the UK it must benefit both the regional distribution companies and their customers. This proves that every case is a different case; the US based experience can not be mimicked in the UK because the structure and conditions in the electricity supply industry differs from that of the USA. The more general approaches of DSM policies may probably be globalised. For different countries DSM policies must be tailored for the specific conditions that apply to them. For example in Kuwait the government represented by the Ministry of Electricity and Water (MEW) is the only body that is in charge of the generation, distribution and supply of electricity. In addition, electricity is supplied to the end users at a highly subsidised price; where MEW carries around 80% of the total cost and the end users are only charged the remaining 20%. In addition Kuwait does not utilise different pricing schemes that would encourage end users to make use of cheap rate periods. In the context of the system in Kuwait, the utilisation of DSM policies would benefit the country on the national basis and not on individual basis. On the other hand, it is possible that at some stage, such subsidy will no longer be feasible and an increase in the charge rate would possibly be introduced. In the mean time, with MEW as the generator, distributor and supplier of electricity in Kuwait, DSM policies would have to be tailored for such specific conditions for such specific time period.

In Nilsson's (2000) review of the definitions of DSM from the International Energy Agency Demand-Side Management Programme (IEA DSM) web site, it becomes clear that DSM is a tool that is owned by several parties and not by only a single body.

"Demand-Side Management (DSM) can be looked upon either traditionally, as a tool to be used to change the demand for energy or more generally, as a tool for society to better use and distribute scarce resources. When implemented by energy utilities, this change might be in the amount of energy used or the pattern of its use. For example, an electric utility may increase the power supply and provide customers with the kWh they ask for or provide better equipment that uses less kWh while providing more service. Or the utility company may seek to change the pattern of energy use by applying straightforward and operationally simple time-of-use pricing to shift the load. In either case, the objective is to choose the best option to provide energy services at the lowest cost.

DSM as a more general tool opens up a broader range of long-term activities which are triggered by society's concern for the environment and desire for sustainable development. This option can be more complex, and it is often supported by other goals and activities, for example, market transformation and the opportunities for the emergence of new type of industry

In both cases, at least as far as this Implementation Agreement is concerned, the main thrust and reason for DSM activities are due to the necessity to increase energy efficiency and receive better value for the capital invested in the energy system".

When the targets are to increase energy efficiency and receive better value for capital invested in energy system; in addition to conserving the natural resources with providing protection to the environment, then DSM policies must be the interest and responsibility of all parties of concern of any of the issues above.

2.3 DSM applied to air-conditioning systems in offices

The majority of the literature available on the subject of DSM has many issues in common. Gellings (1989), Saini (2004), Beggs (1995) and many others express the meaning of DSM in great detail: what DSM means,; the benefits of DSM, the different strategies of DSM. As the aim of this research work is to introduce a DSM operation strategy for air-conditioned office buildings a brief introduction to this application follows.

Although the broad definition of DSM of the EPRI (1984) has many meritsit does not cover the whole target or all the relevant aspects of DSM to specific applications. The notion of DSM that was initiated in the United States was customized to fit the scenario for the specific circumstances that existed for that nation. In contrast, many of the western and European countries worked hard to utilise such concept and so an international frame of DSM developed.It appears that DSM has become an umbrella for many issues that can be covered within the basic concept, for example designing energy efficient buildings, applying energy conservation, energy auditing of existing buildings and the efficient operation and control of building services within a building or a building complex. Increased efficiency, load management and energy conservation, all with the emphasis on reducing the need for electrical energy and/or generation capacity, are what DSM aims for.

2.3.1 Demand Side Management Objectives

The uncertainty in future demand, fuel prices and availability and increase in the cost of power generation and distribution in addition to crucial environmental issues are driving governments and utilities towards the incorporation of DSM strategies. As suggested from the different definitions and explanations discussed previously, DSM encompasses load reduction strategies as well as load growth strategies and flexible energy services options. At the national level in the United States, DSM is expected to make a significant contribution to meeting future demand, figure 2.1, Gellings (1989). Estimates of viable DSM greatly exceed its current levels of application, indicating considerable future potential.

From figure 2.1, it can be predicted that DSM may be rewarding. Without DSM strategies that utilise utility projections of future demand the party in charge of power generation might end up having to construct or expand the power generation facility to be able to supply the demand. However, as the figure shows, with DSM strategies utilisation of the existing capacity and postponing the need for purchasing and installing new plants would help achieve conservation of energy, the environment and most important, would assure financial stability because of the budget saved rather than spent on new constructions.

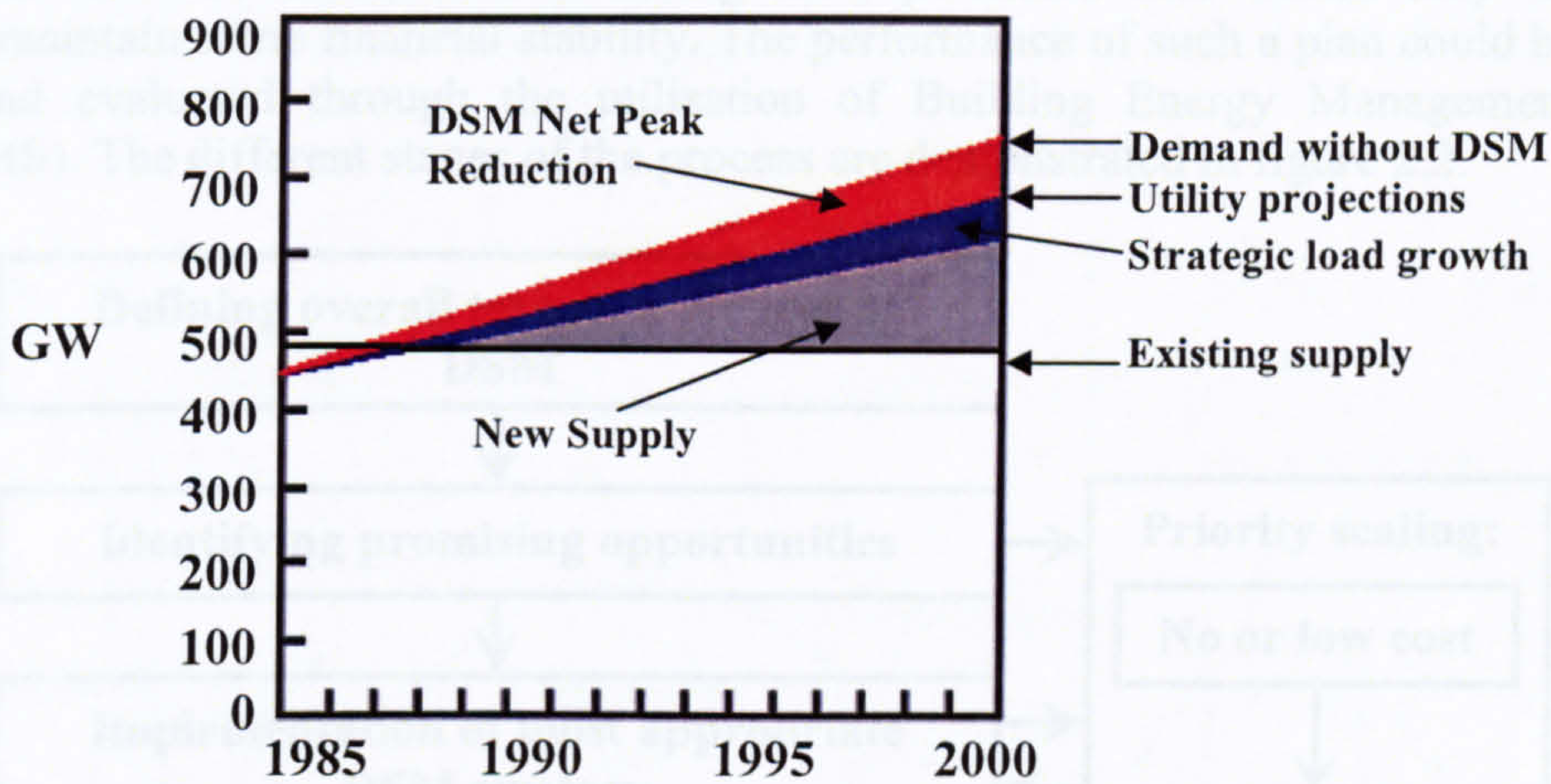

Figure 2.1 DSM's contribution towards meeting future demands, USA

A key objective in deciding for a DSM strategy is defining the overall targets that are to be met by DSM. For such purpose, an action plan that will put such a process in a clear framework is important. Whether DSM strategy is to be targeted by a government at the national level or even by a private institution on much smaller scale, the need for identifying promising opportunities must first be satisfied. This would provide an understanding of the situation and would clearly distinguish whether a demand-side management plan or a supply-side management plan provides the best option. If DSM was considered to be the most appropriate option then the development of a most appropriate DSM strategy would be created. This process may be broken into several stages, starting with simple applications that might be implemented with little or no extra cost, and continuing with the implementation of higher costs options. For example, applying such a process in a commercial building might include managing the existing lighting system with relevance to occupancy and non-occupancy periods or even by associating this service with the utilisation of the daylight available from the exterior. In such a process, a zero cost solution would be expected from the change of behaviour of the occupants only and no purchase or installation of new hardware would be required. A following step could be the replacement of the existing lighting system and the utilisation of energy efficient lighting systems, such as compact fluorescent light bulbs. Further investment might be considered in the application electronic lighting control that responded to occupancy patterns and levels of daylight. Additionally, many other retrofitting processes could be introduced in the form of investment in energy efficient glazing system for windows or the energy efficient control of HVAC system by utilising programmable thermostats. Also, the integration of more advanced systems within a building services system in a building. Energy recovery units or thermal energy storage systems can help shift the load of a building from peak time to a non-peak times of the day.

The first step would be to identify opportunities for improving energy efficiency by conducting energy auditing in the target buildings. Subsequently, the most suitable strategies identified from the audit would be implemented. This is a very important stage within the process, as major saving may be identified. As a consequence the need for new expansion or construction through the utilisation of a DSM strategy would be postponed and this would lead to a saving in expenditure that would help an organisation maintain some financial stability. The performance of such a plan could be monitored and evaluated through the utilisation of Building Energy Management System (BEMS). The different stages of the process are demonstrated in figure 2.2.

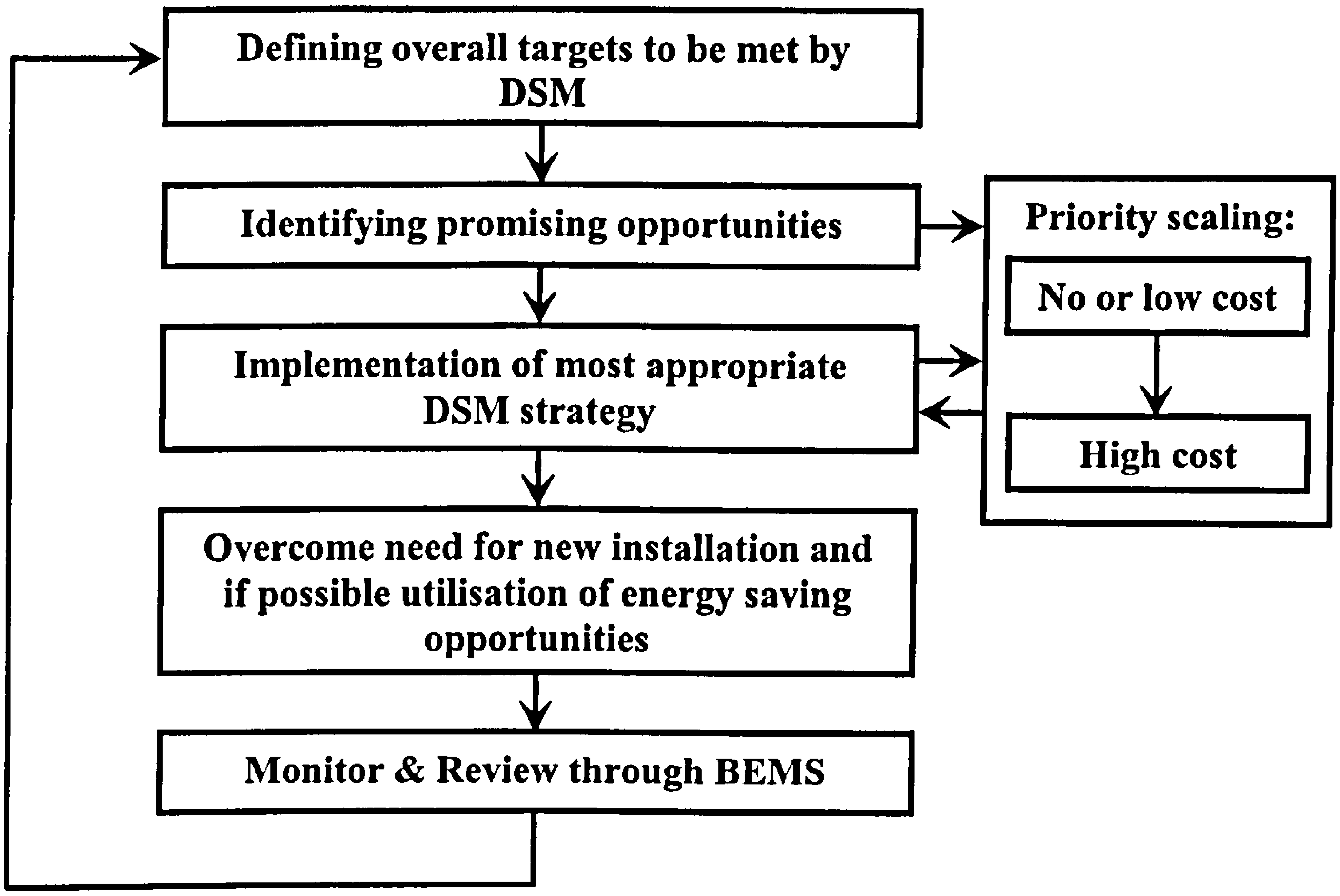

Figure 2.2 Action plan towards a DSM strategy

2.3.2 Demand Side Management & Load Management

Load management is one major form of DSM encompassing only the actions initiated by the utility or its customers as a result of incentives to accomplish peak clipping, valley filling or load shifting. Load management actions are taken to control load growth, altering the load distribution with time or increasing the supply through non-utility or non-traditional sources. The actions may be initiated to reduce capital expenditure, reduce cost of the service, improve load factors, improve system efficiency, or improve system reliability, Gellings (1986).

Load management planning techniques aim to match customer preferences and behaviour to the available electricity supply and to achieve this for the mutual benefit of customer and utility. Planning a load management program has four steps:

I. Choose the daily load distribution changes that the program is to achieve, (figure 2.3)
II. Determine how to achieve the desired load distribution
III. Evaluate costs and impacts
IV. Plan ways to implement the programme

There are six modes by which of load-distribution changes can be achieved: Peak Clipping, Strategic Conservation, Valley filling, Strategic Load Growth, Load Shifting, and Flexible Load Shape, figure 2.3.

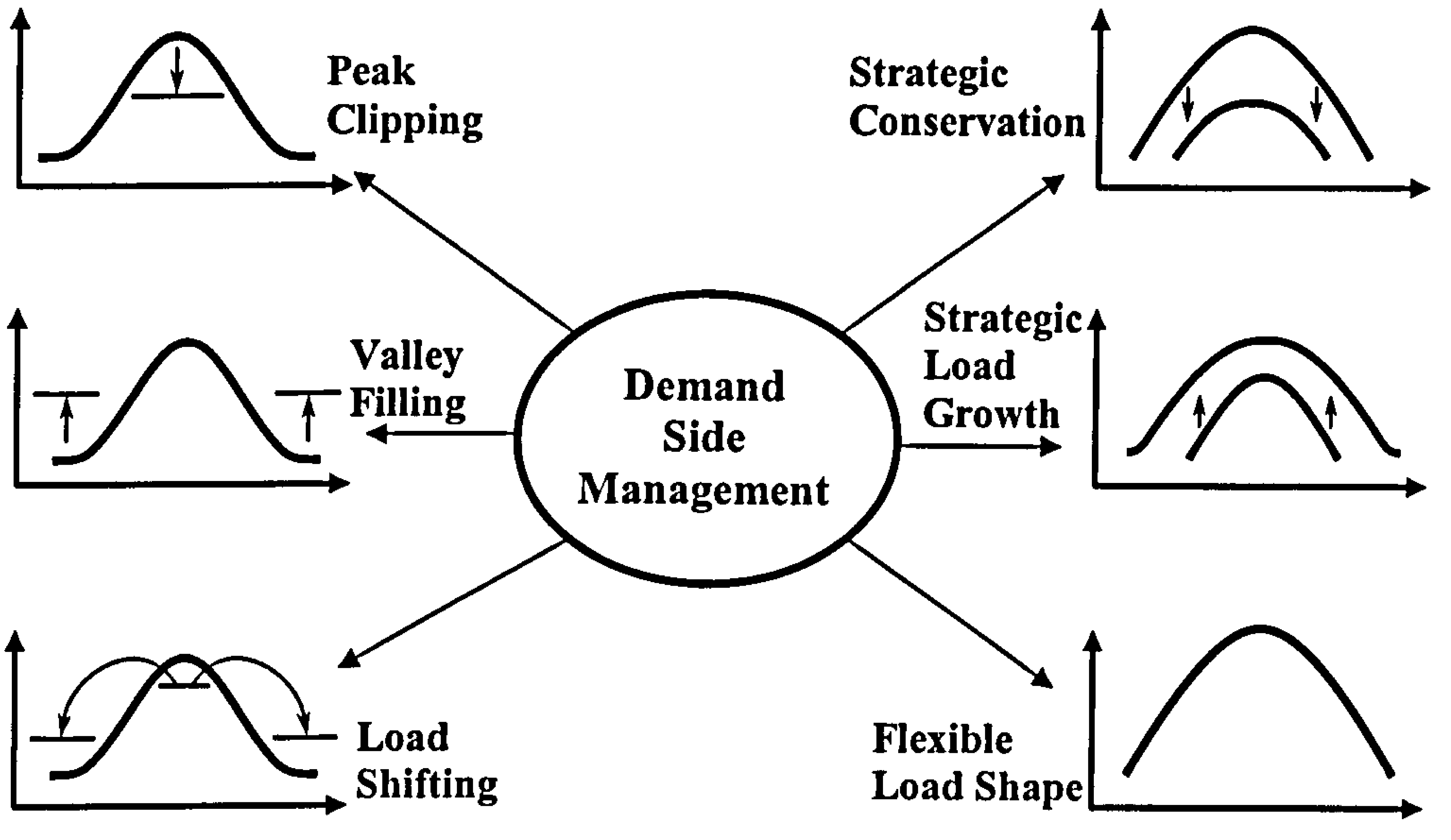

Figure 2.3 Influence of DSM programmes on the shape of demand curve, EPRI 1985

- **Peak clipping**, or reduction of load during peak periods, is generally achieved by directly controlling customer's appliances. This direct control can be used to reduce capacity requirements, operating costs, and dependence on critical fuels.

- **Valley filling**, or building load during off-peak periods, is particularly desirable when the long-run incremental cost is less than the average price of electricity. Adding properly priced off-peak load under those circumstances can decrease the average price.

- **Load shifting**, which accomplishes many of the goals of both peak clipping and valley filling, involves shifting load from on-peak to off-peak periods, allowing the most efficient use of capacity.

- **Strategic conservation** involves a reduction in sales, often including a change in the pattern of use. The utility planner must consider what conservation actions would occur normally and then evaluate the cost-effectiveness of utility programmes intended to accelerate or stimulate conservation actions.

- **Strategic load growth**, a targeted increase in sales, may involve increased market share of loads that are or can be served by competing fuels, as well as development of new markets. In the future, load growth may include greater electrification – electric vehicles, automation, and industrial process heating.

- **Flexible load shape** involves allowing customers to purchase some power at lower than normal reliability. The customer's load-shape will be flexible, depending on the real time reliability conditions.

It appears from the profiles above that both strategic load growth and strategic conservation maintain similar load profiles, however, their effect is to change the quantity of energy consumed over specific period. In the case of buildings strategic conservation mainly can be achieved by installing more thermal insulation in the building structure, employing more energy efficient equipment, or by reducing the hours of use.

Talukdar and Gellings (1986) classified load management activities as: Energy Storage, Interruptible Loads, Conservation, Customer Loads Control and Dispersed Generation (DG). Conservation involves, improving appliances, new energy-efficient building designs, draught proofing buildings, life-style changes and water heating using passive solar systems. Dispersed Generation includes four main activities, solar PV, wind power generation, cogeneration and small hydro generation.

Thermal Energy Storage (TES), in the form of ice storage system, is the basis of this investigation. Thermal (cooling) energy storage is accounted as a load shifting strategy because it involves shifting the load from on-peak to off-peak periods. In the case of ice storage systems, the storage system is charged by producing ice during off-peak periods and then to use that ice to cool the building during peak consumption periods, thus shifting the electricity load. TES will be discussed in the Chapter 4 in greater detail.

According to Rabl (1988), future electricity load distribution patterns will be the result of programmes implemented by the utility companies which are tailored to meet their objectives. DSM can be used not only in terms of load distribution objectives but also to improve the poor load factor caused by reactive loads. The demand for electricity varies throughout the year/day/hour, so that the average utilisation of the available power generating capacity is less than 100%. This is described as the load factor (LF).

The load factor for any given period represents the percentage of time for which plant and equipment operates during that period. It can be calculated as follows, Beggs (2002):

$$Load\,factor\,in\,a\,given\,period = \frac{Average\,load\,on\,system\,[kW]}{Peak\,load\,on\,system\,[kW]} \qquad \textbf{Equation 2.1}$$

Table 2.1 shows some typical load factors which might be expected for a variety of types of organisation, Forrester 1993. Buildings such as air-conditioned commercial offices, with a high daytime peak and low night time demand, will exhibit a low (i.e. poor) load factor. At the other extreme factories which operate a 24 hour shift system will exhibit a high (i.e. good) load factor. From the utility companies' point of view organisations which possess a high load factor are potentially more desirable customers, since they will be buying more electrical energy for a give amount of investment in generation and distribution equipment. Customers who possess high load factor should therefore expect to negotiate better supply contracts than those with low load factors. This provides great potential benefit to contract customers who possess the ability to load shift from day to night by using technologies such as ice thermal storage. This should be particularly true for office buildings which would otherwise exhibit a very poor load factor, Beggs (2002).

Table 2.1Typical load factors for a veriety of applications, Forrester 1993

Type of organisation	Load factor
24 hour operation	0.7-0.85
2 shift system	0.45-0.6
Single shift system	0.25-0.4
Modern hotel complex	0.5-0.6
Hospital	0.6-0.75
Retailing	0.3-0.4
Catering business	0.3-0.5

This research work is concerned with reductions in peak demand levels. Peak clipping, valley filling and load shifting can all be accounted for as peak load reduction measures. However, as the scope and objective of this research work is to introduce a DSM strategy through the optimisation of an ice thermal storage model with an integrated model of a predictive control strategy, load shifting has become the candidate to be the measure investigated. The objective is to achieve this through the use of an intelligent device, *Model Predictive Control* (MPV), which will respond to predicted patterns of demand and work to optimise the ice charging and discharging process.

2.3.3 Benefits of DSM

The many literature sources that have been studied list numerous benefits of DSM programmes. These benefits can provide a return to customer, society and the utility companies. The most common of those benefits are listed below:

1. Customer
    a. Lower bills
    b. Improved services
    c. Non-energy business benefits

2. Society
    a. Capital freed for other projects
    b. Reduced foreign debt
    c. Lower business costs
    d. Reduced pollution
    e. Conservation of indigenous energy resources

3. Utility
    a. Lower cost of services
    b. Less generation and transmission capacity required
    c. Improved operating efficiency
    d. Improved customer service

2.4 Conclusions

Electrical power generation and consumption can logically be divided into two key groups. The supply-side group comprise the electricity utility companies that generate and distribute the electricity are concerned with supplying the demand. The customers that create the demand for electrical power comprise the demand-side group. Electricity supply is created in sufficient quantity to be able to provide for the demand that exists or is expected. The supply-side approach is to be able to provide the demand through the construction and installation of power generation plants that have the sufficient capacity to provide the instantaneous electricity demand required by the customers. However, such an approach is always accompanied by major spending on the expansion of power generation plants, increased cost of services and often a decline in operating efficiency. In addition, such an approach would negatively affect supply-side companies who would have to carry the cost to provide sufficient available capacity. One possible consequence would be an increase in the cost of energy purchased by the customer leading to increased bills. Finally, such an approach has a potentially negative effect on the environment. Consequently, DSM was developed in the form of strategies and policies that aimed to cope with the current and future demand by optimising the use of the currently available generation capacities and postpone as much as possible the need for constructing new power plants.

Demand-side management offers utilities the opportunity to address several operational and management issues – improvement of power quality and reliability, reduction of system losses, easing transmission network constraints etc. DSM is feasible in situations where the cost of DSM is lower than the cost of supply. It is often used as a part of capacity expansion management strategies and in situations of supply capacity shortfall. It is important to highlight that DSM is not partial and its benefits are extended to the supply-side, customers and the environment.

In Kuwait, DSM is in its infancy. Initial steps towards dealing with the rapidly growing demand for electrical power are being considered and some basic applications have already taken place. In the following chapter, an overview of the electricity supply industry in Kuwait is given. Initial application of DSM through energy conservation measures, energy auditing towards reducing the consumption of electricity and other energy efficiency measure are listed through some examples related to the Kuwaiti context.

"The great investments which the country spends in the field of electrical power generation and water desalination should make the consumers aware of their responsibility in following a rationalisation consumptive attitude and not to take the opportunity prompted and encouraged by the very cheap price of electricity (supported by the government) to waste this valuable wealth. This action wastes the wealth and capacities of the country and increases the rates of demand on electricity and water in unreasonable and exaggerated rates. So everyone should know the fact that the government will not be able to continue support the prices of this service forever while there is no consumptive awareness by the consumers" ... Minister of Electricity & Water - Kuwait

Chapter 3

The Electricity Supply Industry in Kuwait

3.1 Introduction

Global developments and technological progress during the twentieth century has been associated with massive urban expansion. Large buildings, shopping areas, hospitals, and schools necessitated the adoption of indoor air conditioning systems. Urban developments in Kuwait and the Gulf States were also associated with extensive use of indoor air conditioning. This is because of the long duration of the hot summer season, which extends for more than 7 months during which long spells of high temperature and high humidity conditions are encountered. Considering the above, a major part of the energy consumed in Kuwait and the Gulf States is due to indoor air conditioning. In its energy conservation programme code of practice guide, MEW (1999-B) states that "Air conditioning installations absorb 60 to 70 percent of the consumed energy. As a result, the need for the construction of new power plants is permanent to satisfy this continually growing need.

Kuwait holds proved crude oil reserves of about 98 billion barrels that represents about 10% of world reserves, CIA. The state has five power stations and a total generation capacity of about 9.3 GW. A 2,400 MW thermal plant with a construction cost of $2.2 billion was the last that came online in the year 2000, which relieved pressure on the grid connected system in the short term. Over the next 10 years, Kuwait reportedly will need to invest $4 billion in its power supply sector in order to increase generation capacity by another 3,400 MW, EIA. In September 2001, the government represented by the Ministry of Electricity and Water (MEW) approved the construction of two power plants under this program. A 2,400-MW station is to be installed at one location (Al-Zour North); and the 1,000-MW will be installed at another location (Al-Zour South II). Both installations are expansions to the national power grid system in Kuwait.

Heating, Ventilation and Air-Conditioning (HVAC) systems have become a necessity for the modern life style. Air conditioning can play several roles to reduce the environmental impact of buildings. A building has to be suitable for its purpose and the indoor climate must be comfortable and healthy, and there should be minimum disturbance when the building is in operation, CADDET 19 (1996). Many countries that suffer from hot arid climates cannot escape the need for using air conditioning systems. Kuwait is one of many countries in the world that rely heavily on air-conditioning systems for the cooling of buildings. In such circumstances, the utilisation of HVAC systems can lead to the introduction of two important issues that should be of concern to governments, private and public power generation companies as well as building owners. First, would be that the use of indoor climate conditioning systems affect the different aspects of energy production and consumption on national level? The second issue is, what effect the operation of such systems has on the running cost of buildings and the cost of power generation at the national level. Both issues are linked together and cannot be separated from each other. HVAC systems are recognised as a major contributor to the power consumption and demand on national level and so the development and utilisation of energy efficient control strategies has become of national interest. Motivated by the rising electricity generation cost, which is represented by the growing consumption and the need for constructing new power plants; the need for devising and enforcing *Demand Side Management* (DSM) plans in the form of energy efficient operation strategies to curtail the excessive consumption of energy in air-conditioned buildings has been established. Adopting such strategies would not only lead to optimising the use of air-conditioning systems, it would also lead to large savings in the operation and running cost of such systems. Additionally, it would slow down the rate of construction of new power plants that arises mainly from the growth in power demand for air-conditioning.

Examining methods for controlling the electricity demand in Kuwait is the main objective of this research work. This is by means of employing state of the art DSM techniques. In order to fully comprehend the aims and objectives of this research work, it is necessary describe the characteristics of the electricity supply industry in Kuwait. Focussing on the problem of power and energy in Kuwait due to the usage of air-conditioning systems, this chapter reflects upon the reasons that originated the objectives of this research work.

3.2 Patterns of Electricity Consumption in Kuwait

Kuwait has experienced an economic boom ever since the commencement of oil production in early 1950s. This boom reached disproportionate levels in the late 1970s, following the rise in oil prices and the attendant increase in national revenue. Consequently, a rapid expansion in construction and development was manifest in addition to increasing demand for electrical energy. Kuwait is accounted as one of the energy exporting nations and is endowed with large reserves of oil and natural gas. Over the past few decades, electrical power generation and water desalination facilities have grown to be the biggest energy consumer, Kellow (1989).

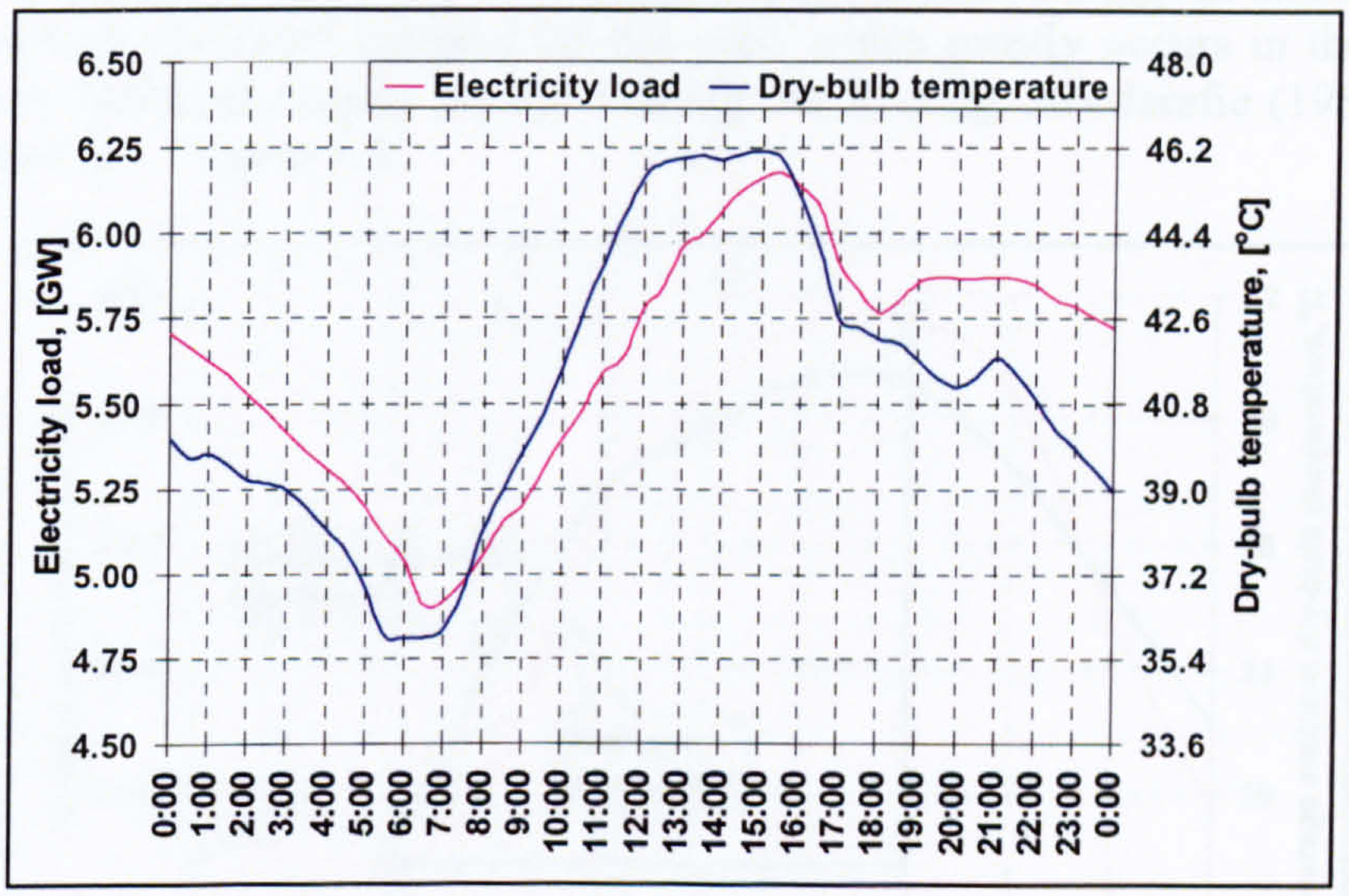

Figure 3.1 Peak daily power consumption rate and ambient temperature for Kuwait for 4th September 1999

Kuwait has a long, dry and hostile summer that extends over seven months from April to October. It suffers from severe climatic conditions with peak daytime temperatures varying between 43°C - 53°C. Consequently, extensive use of air-conditioning systems occurs in buildings during that period for cooling purposes. Figure 2.1 shows the variation of power consumption rate for Kuwait and the ambient temperature distribution for a September day in 1999. These patterns are typical for all days during the summer period.

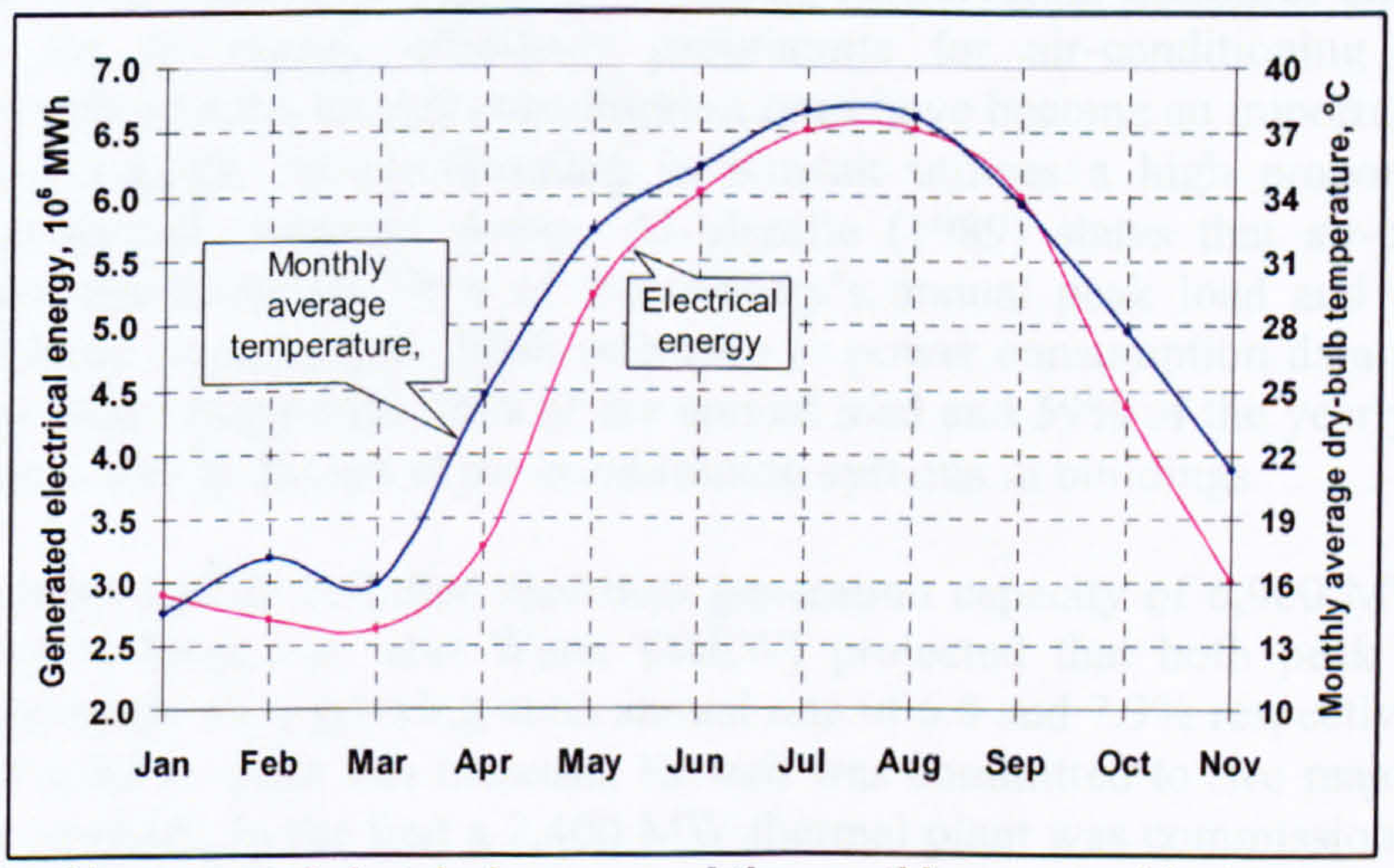

Figure 3.2 Monthly generated electrical energy and the monthly mean ambient temperature for Kuwait 1996

Similarly, the total quantity of electrical energy generated for consumption each month for Kuwait is influenced directly by the monthly mean ambient temperature, figure 3.2. The peak power demand in Kuwait occurs between 1400 and 1600 hours during the peak of the summer season. Quantitatively, peak power demand for air conditioning is indicated by the difference in the average maximum demand during the summer months and the average minimum demand for the year, which mostly occurs in the month of March when buildings require neither cooling nor heating, Al-Marafie (1989). This is demonstrated by figure 3.3.

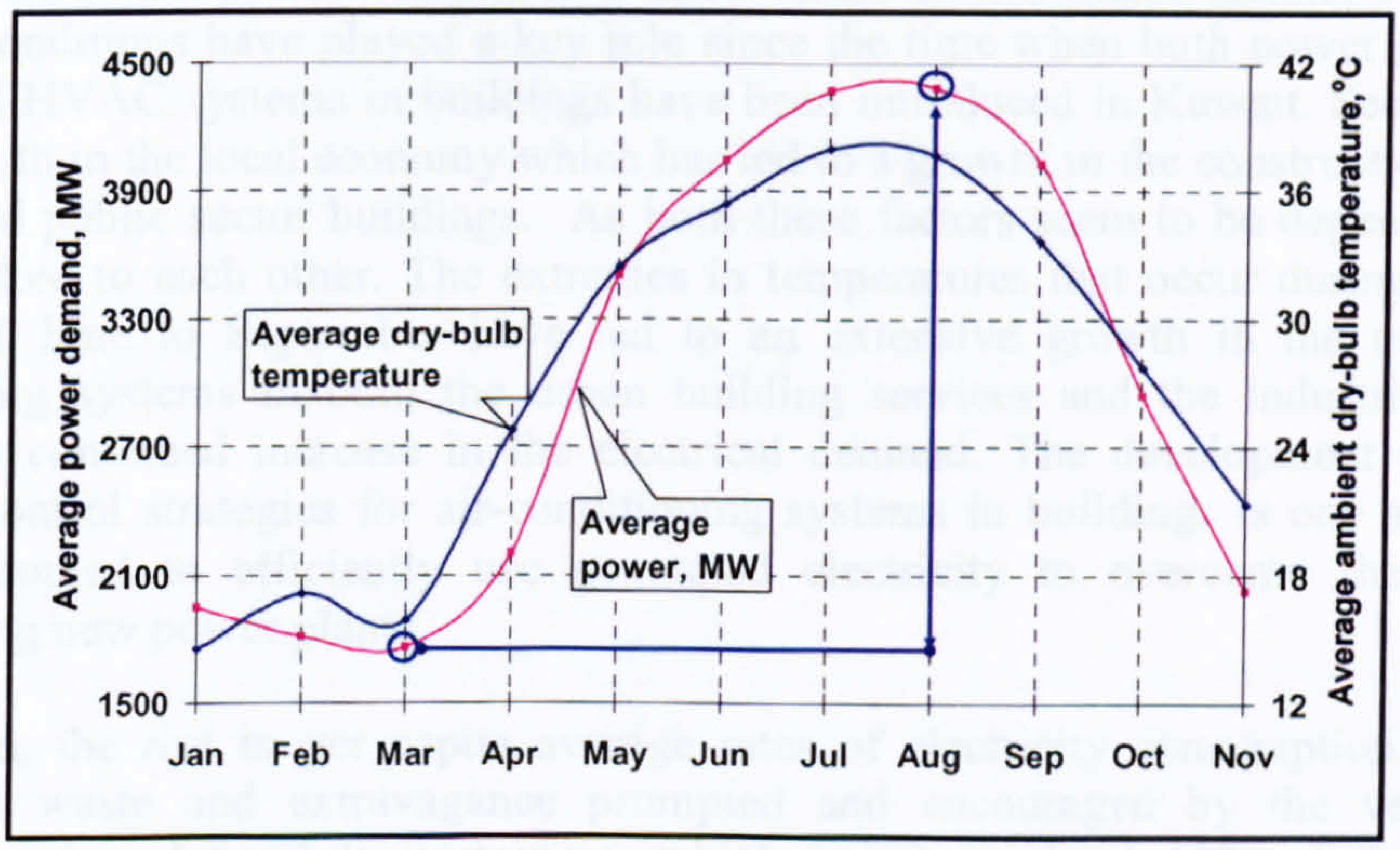

Figure 3.3 Peak power demand related to air conditioning for Kuwait, 1996

Measures for energy conservation in buildings have been implemented in Kuwait since 1983. The Ministry of Electricity and Water (MEW) have published a well-defined code of practice regarding energy conservation matters, Maheshwari (1998-A). However, much has changed since that time but the code has not been updated to include current issues or requirements. At present, buildings in Kuwait consume excessive amounts of energy due to the absence of up to date energy conservation measures and of a clear framework for an energy efficiency programme for air-conditioning systems in buildings. Consequently, energy consumption rates have become an important issue that must be investigated. Air-conditioning in Kuwait utilises a high proportion of the country's generated electrical power. Al-Marafie (1989) states that air-conditioning accounts for approximately 70% of the country's annual peak load and 45% of the yearly electricity consumption. With reference to power consumption data for the year 1999, it was found that nearly 75% of the annual load and 59% of the yearly electricity consumption is due to the use of air-conditioning systems in buildings.

In 1997, Kuwait had an installed electrical generation capacity of 6,900 MW. In 1998 the Ministry of Electricity and Water (MEW) projected that both peak power and electricity demands were growing at an annual rate of 6.8 and 7.3% respectively, (MEW 1999-A). In order to meet this increase, Kuwait was committed to two major electrical power plant projects. In the first a 2,400 MW thermal plant was commissioned to begin operation between 1998 and 2000. The second project relates to a new thermal power plant, which includes a seawater desalination plant to produce 48 million gallons of fresh water per day. At present, new and former power stations in Kuwait add up to a total capacity of 9,273 MW in the form of installed capacity. Electricity peak demand has been increasing steadily. The rate of increase during the 20th century ranged from around 32% per annum in the fifties, to 26% in the sixties, 15% in the seventies and 8% in the eighties and nineties. Even though lower rates of increase have been noticed during the past few years, yet, by world standards a range of 8 – 10% is still considered high when compared to 2-3% for most industrial countries, MEW (2002).

The increase in the power demand is a direct result of two major factors. First, harsh climatic conditions have played a key role since the time when both power generation plants and HVAC systems in buildings have been introduced in Kuwait. Second is the rapid growth in the local economy which has led to a growth in the construction of both private and public sector buildings. As both these factors seem to be dependent, they can be linked to each other. The extremes in temperatures that occur during the peak months of June to September have led to an extensive growth in the use of air-conditioning systems in both the urban building services and the industrial sectors leading to continued increase in the electrical demand. The development of energy efficient control strategies for air-conditioning systems in buildings is one action that can be adopted to efficiently use generated electricity to overcome the need of constructing new power plants.

In addition, the rise in per capita average rates of electricity consumption indicates aspects of waste and extravagance prompted and encouraged by the very cheap electricity price charged to customers, which is set at about 11% of the cost of generation. This considerable subsidising of the price of electricity has its historical origins in a policy decision by the Kuwaiti government to help the residents of Kuwait to pay for this essential commodity, Debs (1984). However, this extremely low cost to the consumer has encouraged them to use this utility in an undisciplined and profligate manner.

In some parts of the world, private companies take care of electricity generation and distribution. In Kuwait the government, represented by the Ministry of Electricity and Water (MEW), takes responsibility for generating and supplying electricity to customers. Because MEW heavily subsidises the price of electricity and does not make use of daily price tariffs schemes there is no incentive for customers to manage demand for the benefit of the electricity generating system. The lack of policy regarding the management of the patterns of the rates of electrical consumption has inevitably led to an increase in the annual and daily peak demands. Current rates of demand growth at the summer peak indicate that the annual maximum-load will tend to exceed the installed electricity generating capacity every few years, figure 3.4. Consequently, an almost continual need for the construction and installation of new electricity generating plant has arisen. It is likely that at some stage a new pricing scheme will have to be introduced.

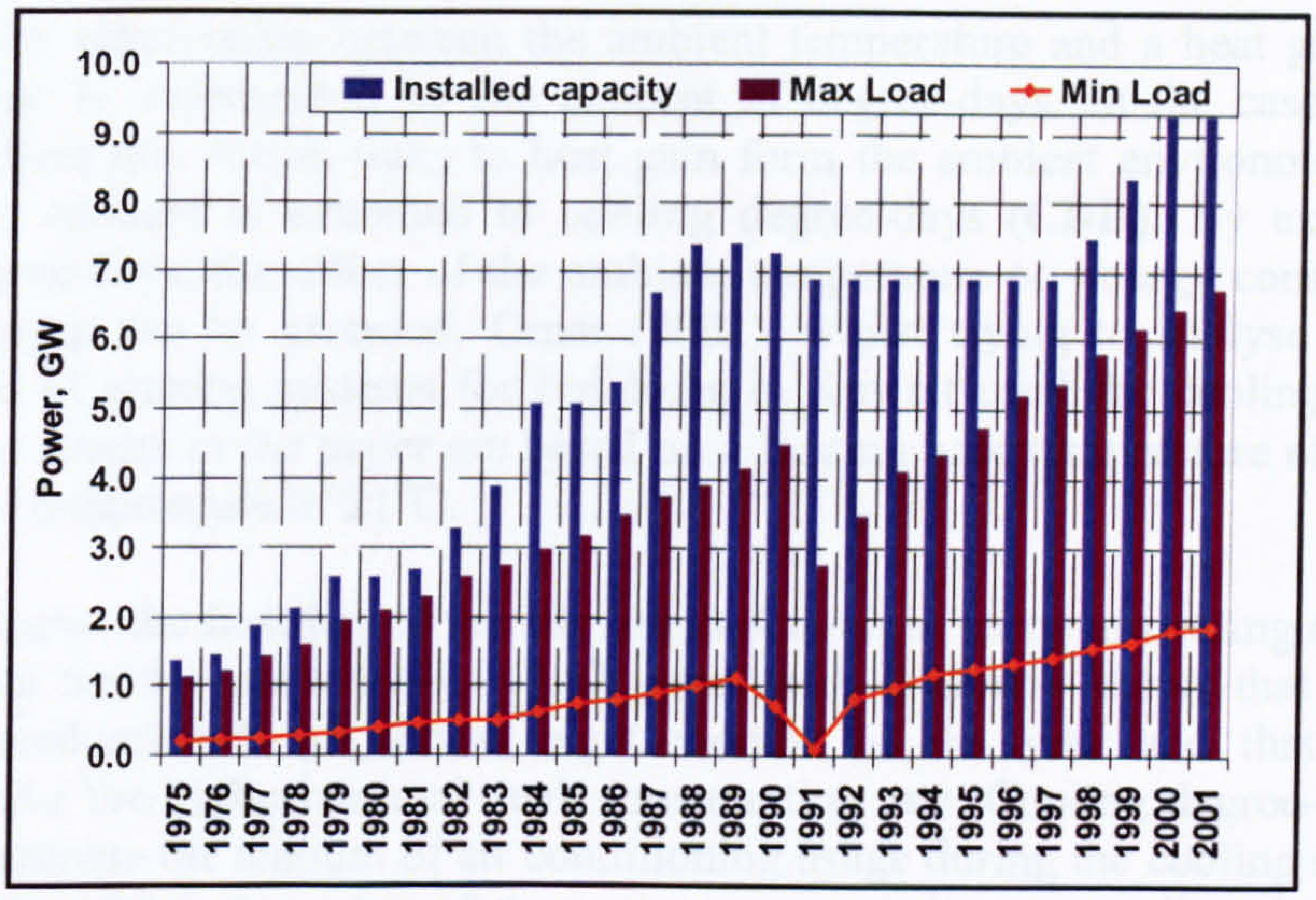

Figure 3.4 Maximum and minimum loads and total installed capacity of electricity generation in Kuwait, 1975 – 2001

3.2.1 Climate Characteristics in Kuwait

High ambient temperature is an important characteristic of summer weather conditions in Kuwait. During the period of May to September, the minimum temperature rarely drops below 25°C, whereas the maximum temperature can exceed 50°C. Such weather conditions require intensive use of air-conditioning in occupied spaces, Ayyash. Figure 3.5, shows the monthly averaged daily maximum and minimum temperatures for the period 1961 – 1990, WMO.

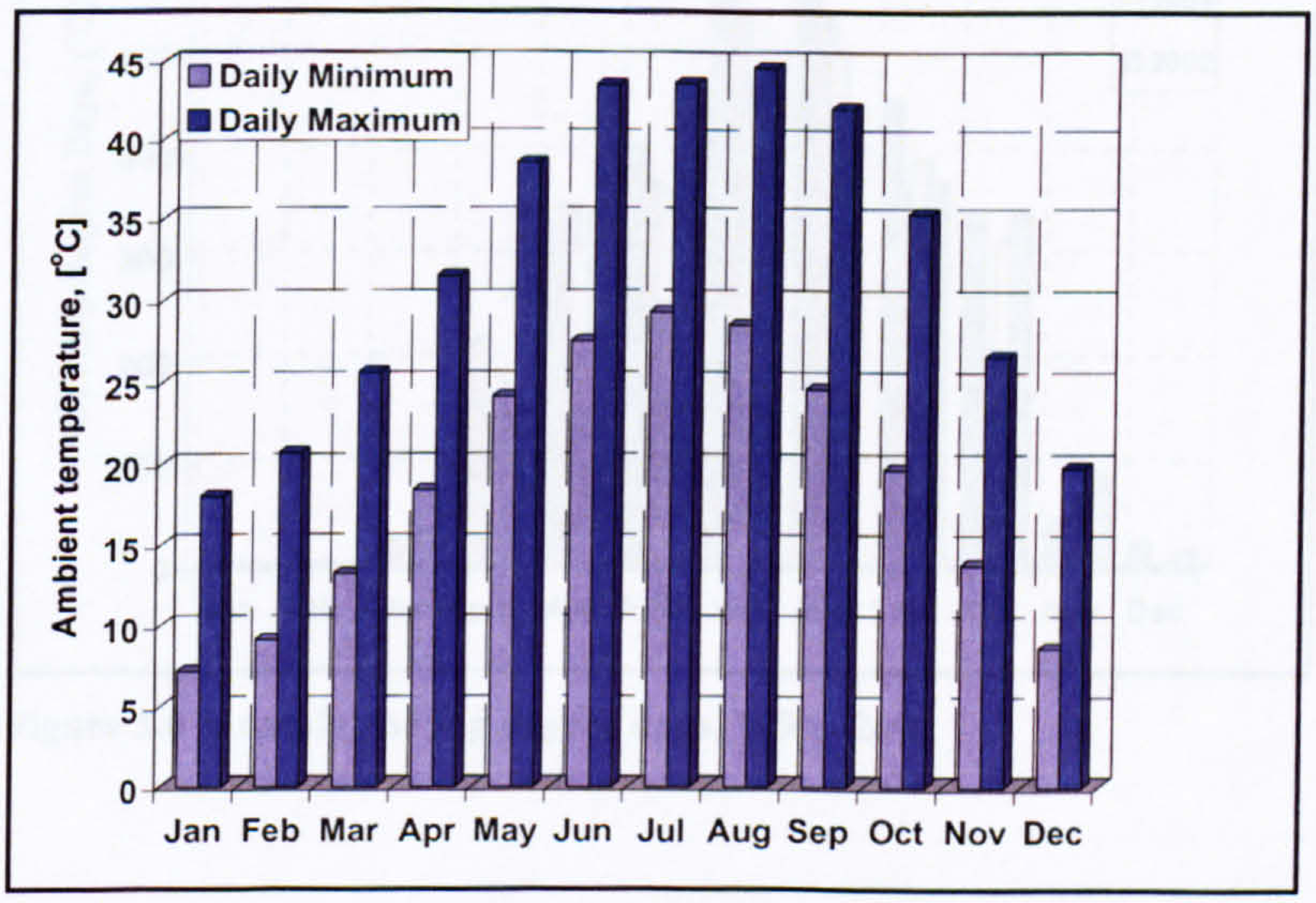

Figure 3.5 Mean daily maximum & minimum temperatures, 1961 - 1990

The temperature difference between an internal building temperature and outside ambient temperature is the driving force that determines heat gain or heat loss for the structure. The relationship between the ambient temperature and a heat gain effect on buildings can be represented by the concept of degree-days. In the case of hot arid counties, where this notion links to heat gain form the ambient environment, then the degree days concept is extended to cooling degree-days **(CDD)**. By examining the cooling degree-days, the effect of the ambient temperature on energy consumption for air-conditioning can be assessed. Omar (2002), whilst trying to analyse the thermal performance of glazing systems for buildings in Kuwait used the cooling degree-day method. The results in the paper are based on a heating base temperature of 18°C and a cooling base temperature of 21°C.

Figure 3.6 shows the hostility of the climate in Kuwait in terms of cooling degree-days. Weather data for the years 1999 - 2002 were used. It clearly shows that the cooling season is predominant for almost eight months of the year and that cooling is responsible for the highest annual peak consumption rate. Cooling degree-days can be utilised to estimate the amount of air conditioning usage during the cooling season. This means that the higher the value of the energy consumption per cooling degree-day the bigger the demand for cooling. Consequently, the consumption of electricity increases resulting in a bigger demand on the national electrical power generating capacity. Figure 3.7 illustrates the growing demand for electricity during a period of four years, 1996 - 1999. For each year cooling degree-days are at their peak during the summer months, July and August, whilst they are at their lowest during the months of March and November. It is essential to make sure that the data used in the investigation have the same characteristics and represents a similar environment.

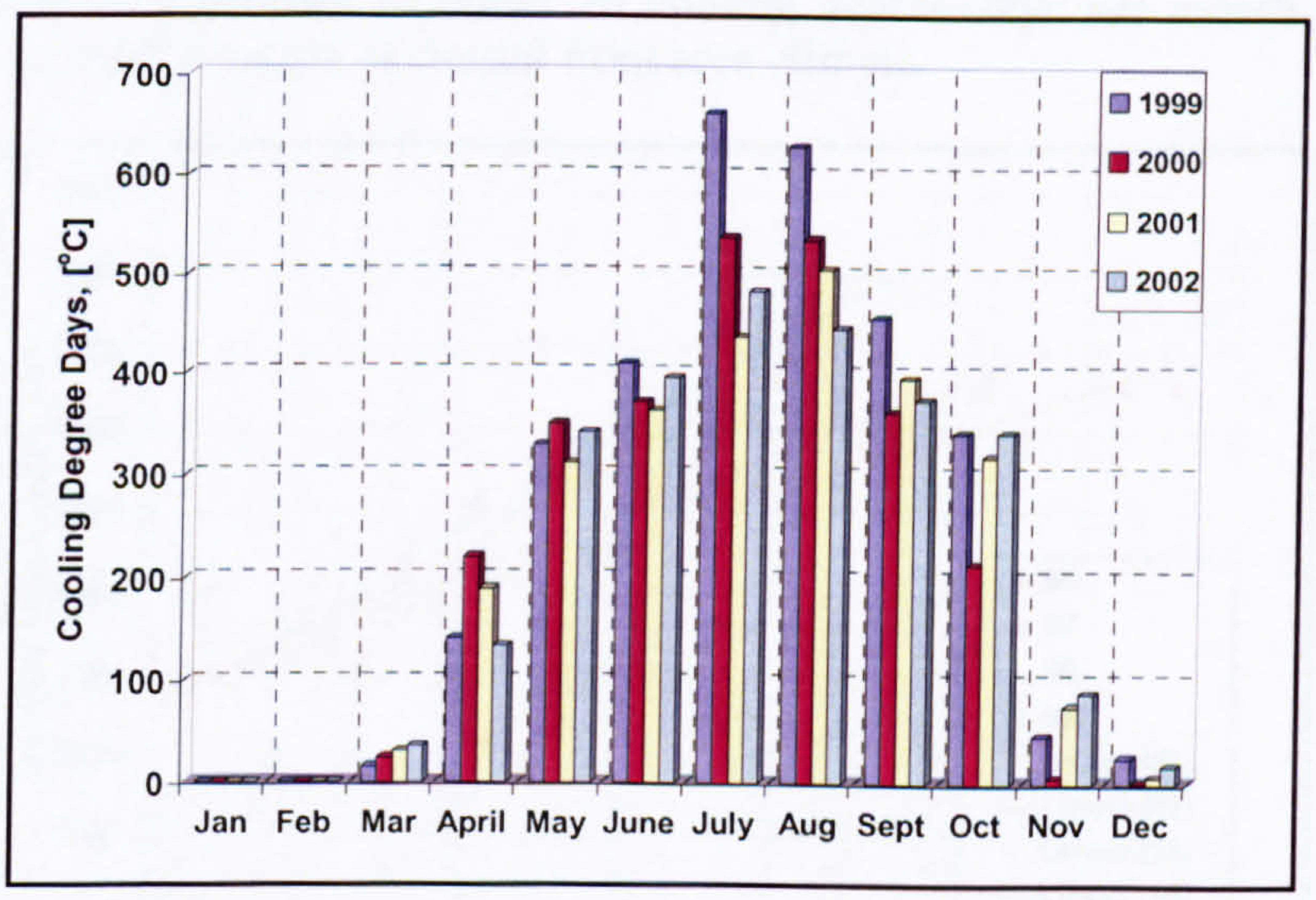

Figure 3.6 Monthly cooling degree days, 1999 - 2002

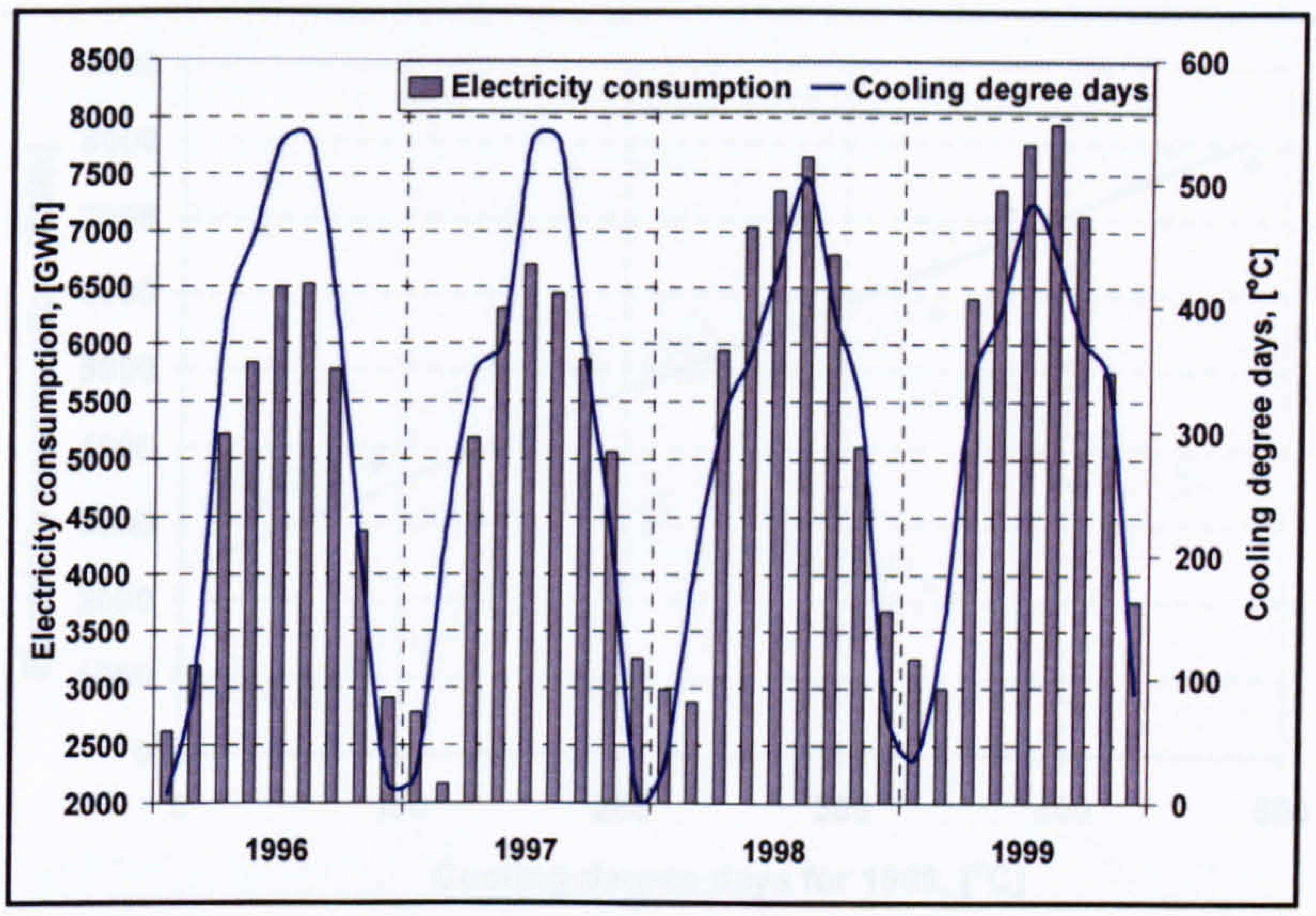

Figure 3.7 Monthly electricity consumption with cooling degree days between 1996 - 1999

A noticeable dissimilarity in the monthly total cooling degree-days for each year can be seen within the same figure. The number of cooling degree-days per month are higher during 96 and 97 whereas the second period of 98 and 99 shows a slightly lower profile. Weather data for 96 and 97 were collected from an internal regional weather station. While, for the years 98 and 99 data where collected from a weather station located in a coastal region. A difference of about 30 cooling degree-days per month is observed because of the milder nature of coastal front area climate.

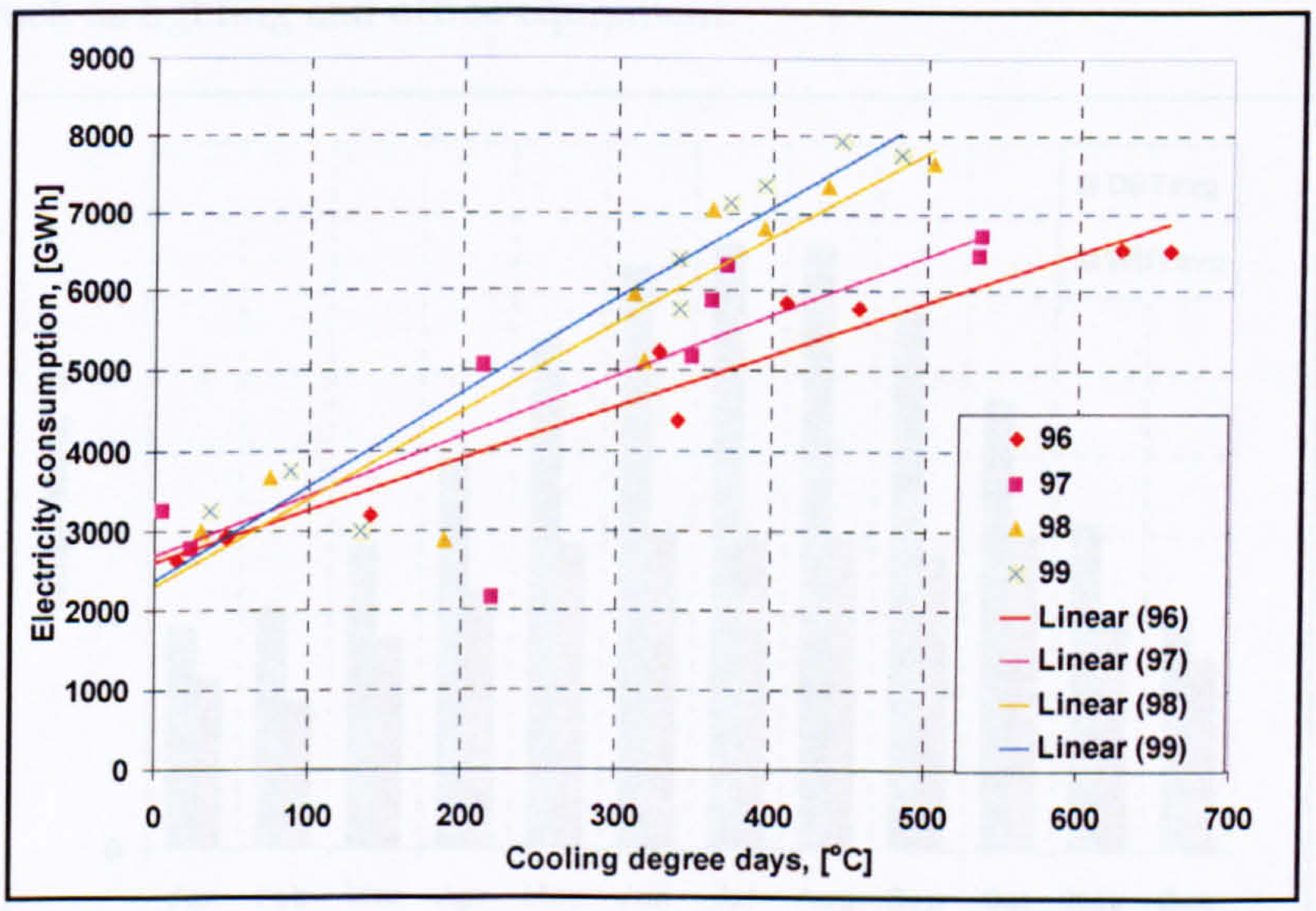

Figure 3.8 Effect of cooling degree days on electricity consumption, 1996 – 1999

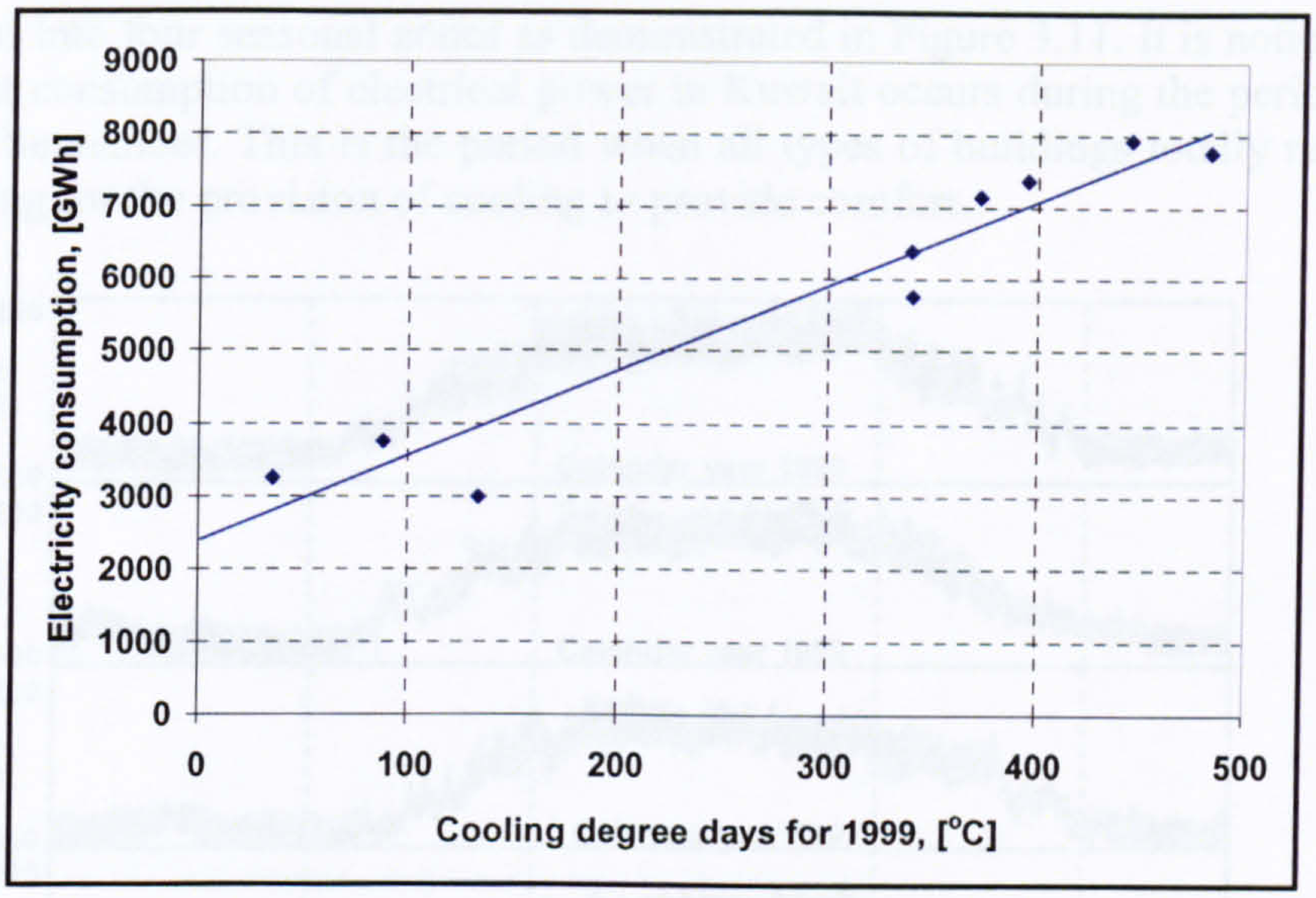

Figure 3.9 Effect of cooling degree days on electricity consumption, 1999

It is rational to link the power demand with the cooling degree-days. The number of cooling degree-days experienced per month is proportional to the energy use of a building for cooling. Examining the graphs of figure 3.8 and figure 3.9, it can be understood why power demand in a country like Kuwait is largest during the months of summer, figure 3.8. During the month of March, the electrical load is at its minimum. From figure 3.9 it can be assumed that during the stated month, no cooling or heating is required and the minimum load that can be attributed to non-climate related loads in a building, such as lighting and office equipment.

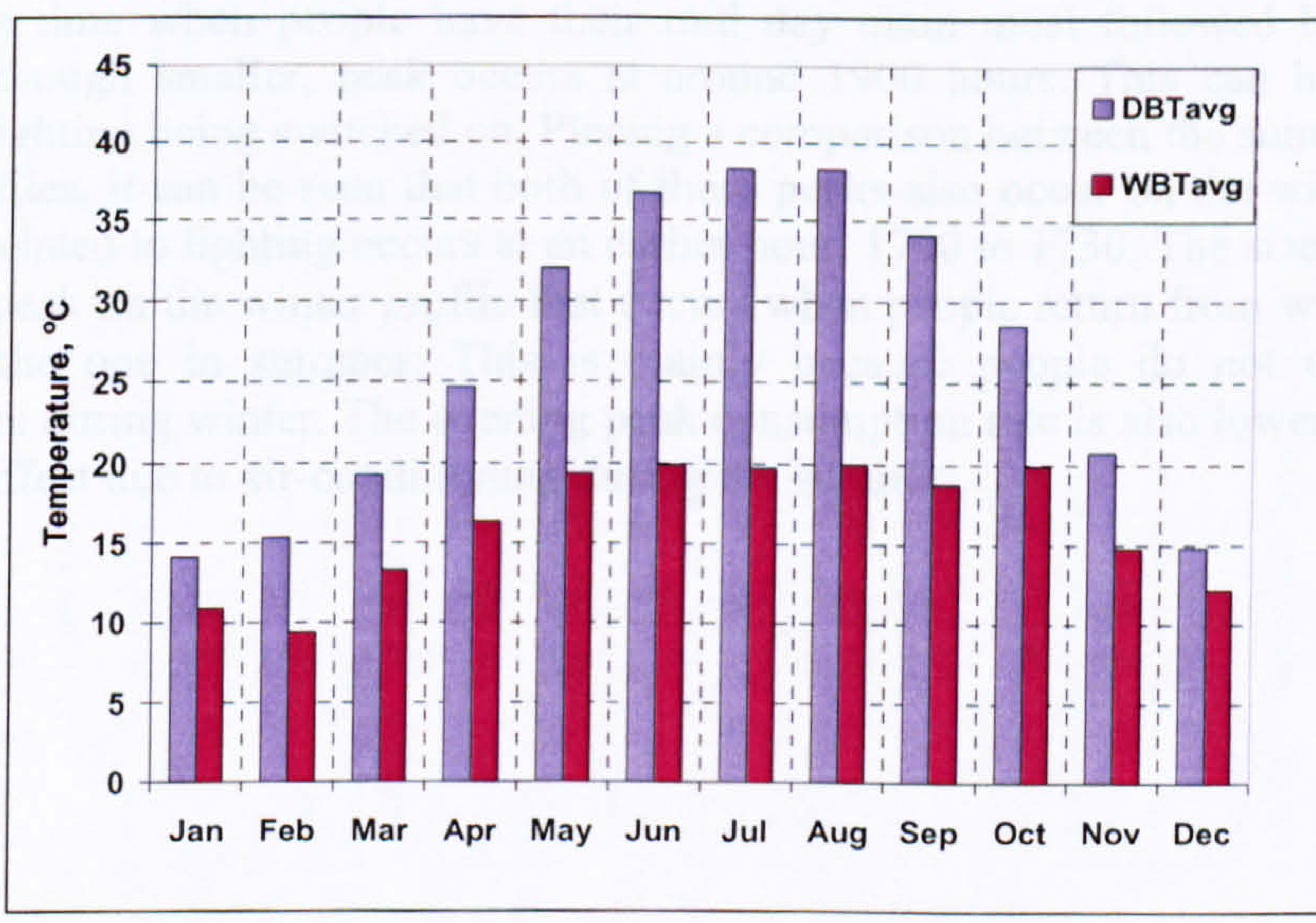

Figure 3.10 Monthly average dry and wet bulb temperature in Kuwait, 1996

The large differences that occur between the dry and wet bulb temperatures through out the year, as shown in , reflect the dry nature of Kuwaiti weather. Alsayegh (2003) splits up the year into four seasonal zones as demonstrated in Figure 3.11. It is noticeable that the highest consumption of electrical power in Kuwait occurs during the period of June to mid of September. This is the period when all types of buildings totally rely on air-conditioning for the provision of cooling to provide comfort.

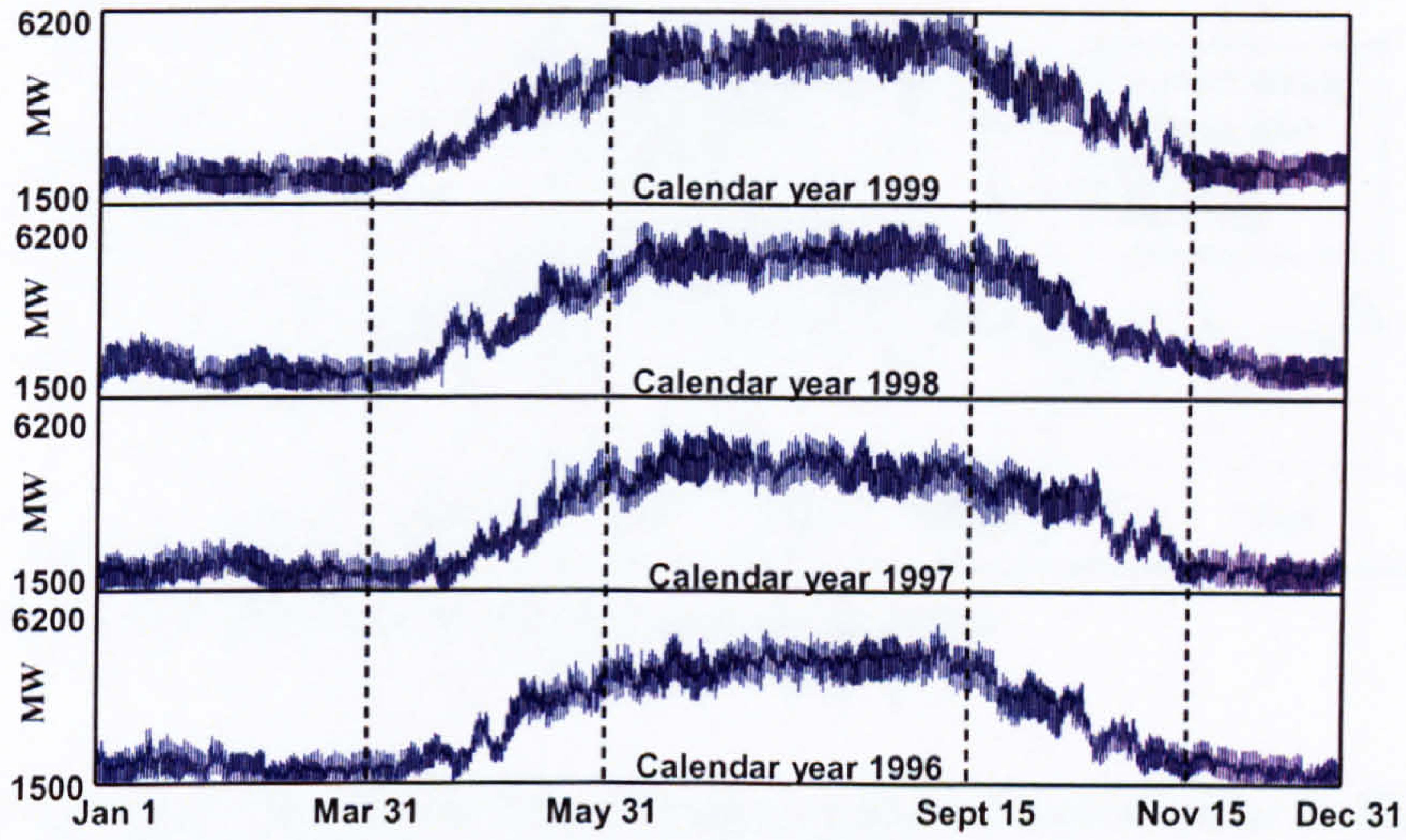

Figure 3.11 Half hourly daily load over the period 1996 - 1999

The difference between summer and winter half-hour profiles is demonstrated in figure 3.12. During the summer season, the maximum peak takes place between the hours 1500 and 1530. This is the time when the peaks of the ambient temperature occur and air-conditioning systems are working at high capacity to provide the cooling required. In Kuwait, people usually return home from work between the hours 1400 and 1500. This is the time when people have their mid day main meal followed by a nap. A second, although smaller, peak occurs at around 1900 hours. This can be related to electrical lighting being switched on. Placing a comparison between the summer and the winter profiles, it can be seen that both of these peaks also occur on the winter profile. The peak related to lighting occurs at an earlier hour, 1700 to 1730. The size of the mid-afternoon peak on the winter profile that occurs when people return from work is much less than the one in summer. This is mainly because people do not use the air-conditioners during winter. The evening peak consumption rate is also lower suggesting a marked effect due to air-conditioning during the summer.

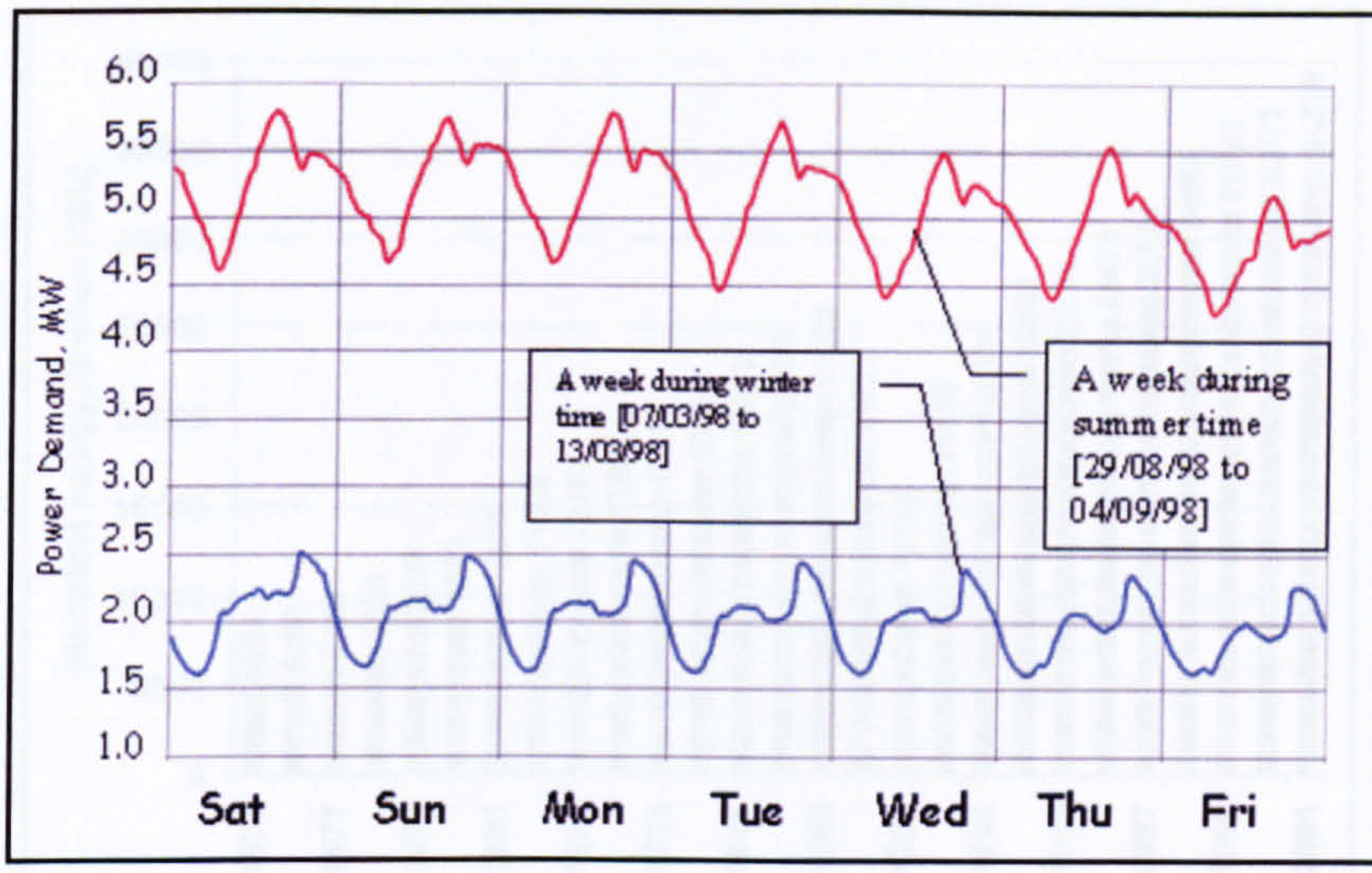

Figure 3.12 Half hourly profiles for summer and winter

3.2.2 Economic Growth and the Change in Built Environment in Kuwait

The effects of the discovery of oil in Kuwait began to become noticeable during the early 1960s with a consequent growth of the oil industry. Revenues increased with the commencement of oil exports to other parts of the world. In turn this allowed increasing public services sector expenditure. Additionally, a noticeable revival in the commercial and contracting sectors occurred. Eventually, Kuwait witnessed a continual annual expansion in construction and urban development. This was accompanied by noticeable growth in demand for electrical energy to the extent that construction of new big power plants has existed and still constantly exists. Growth in the installed capacity and generated energy can be seen in both figure 3.13 and figure 3.14 below.

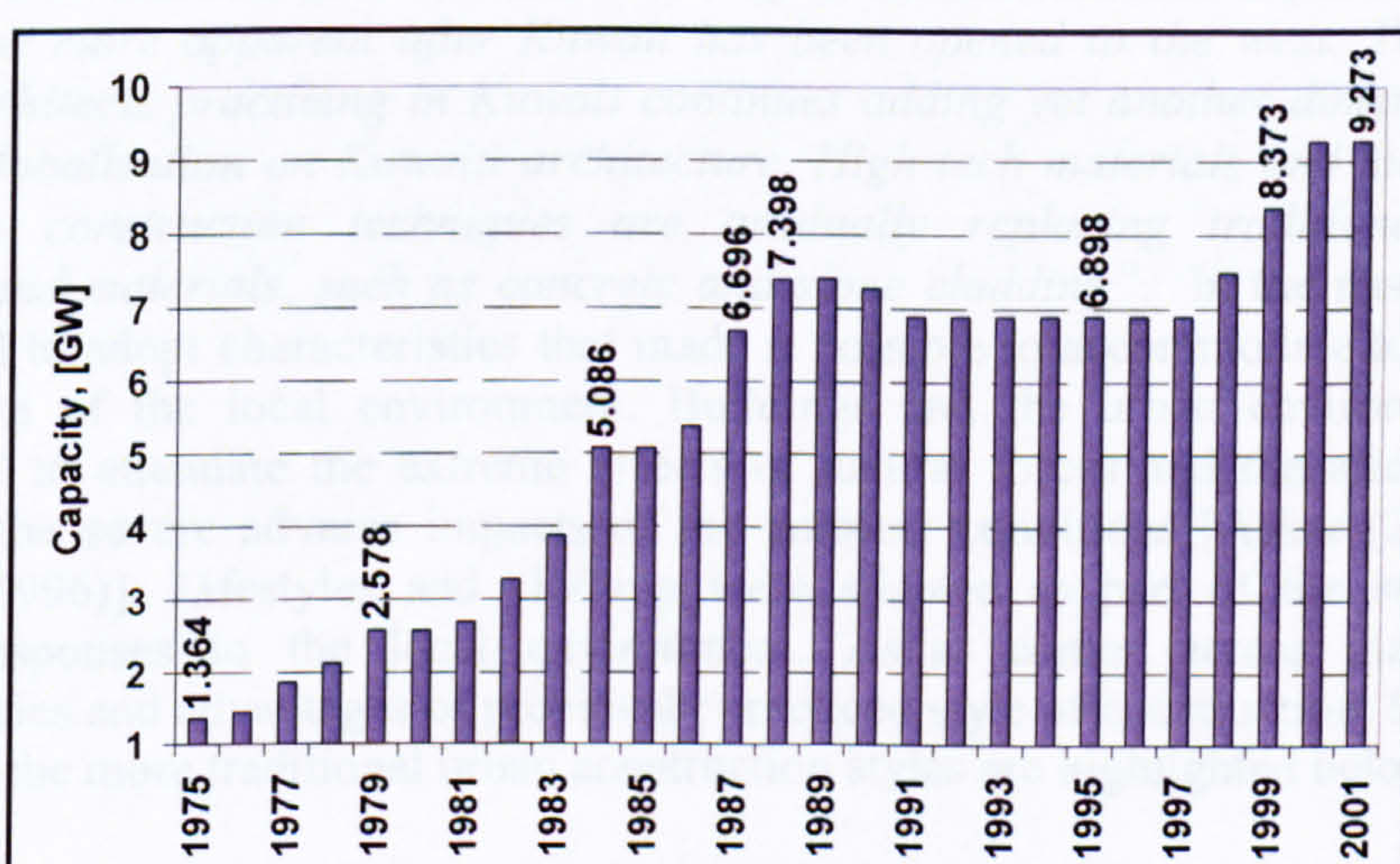

Figure 3.13 Development of total installed capacity for the period 1975 - 2001

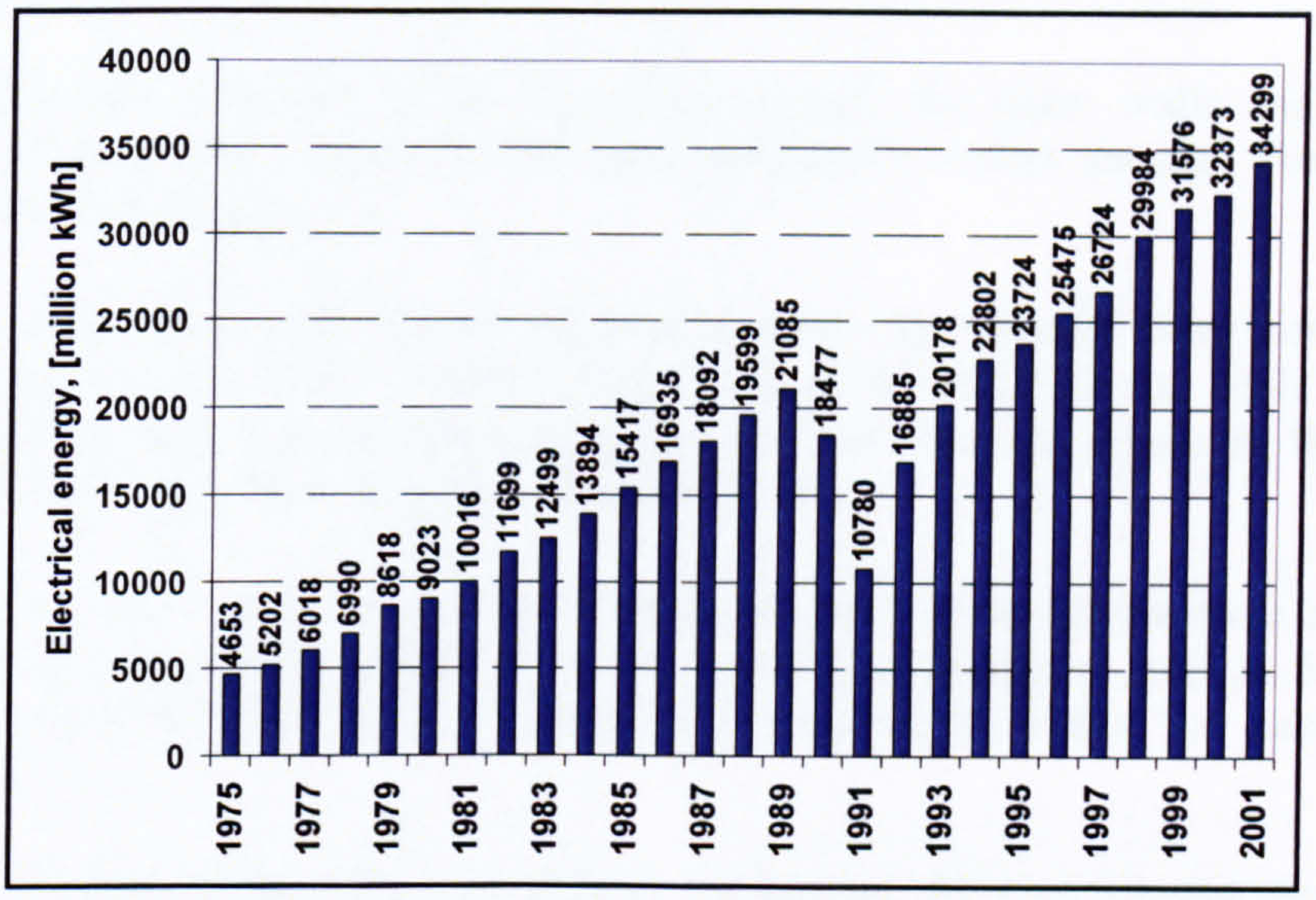

Figure 3.14 Generated electrical energy for the period 1975 - 2001

Moving from a local towards global economy was one of the major economic effects resulting from the discovery of oil and consequently the initiation of the commercial channels with the international world in the form of oil exports. This turning outwards meant that modernist and international style architecture influenced the design of many buildings in Kuwait during the 1970s and 1980s, Khattab (2001). From traditional heavy thermal mass buildings, both the Kuwaiti public and the private sector companies moved towards a modernist light-weight fashion of buildings.

In his paper, Khattab tries to compare some examples of contemporary architecture in Kuwait with earlier forms; He tries to examine the influence of western architecture on their design. While trying to highlight the effect of globalisation on the local architecture of Kuwait, he states that *"The effect of international architectural styles has become more apparent after Kuwait has been opened to the west. The influx of foreign architects practicing in Kuwait continues adding yet another dimension to the effect of globalisation on Kuwaiti architecture. High tech materials and modern, non-indigenous construction techniques are gradually replacing traditional building practices and materials, such as concrete and stone cladding".* In the past, buildings forms used to adopt characteristics that made it possible to accommodate to the terrain and climate of the local environment. Buildings and the urban environment were customised to attenuate the extreme effects of natural forces and the arid terrain by offsetting the severe adverse impacts of the ambient conditions [Askar (2001), from Fletcher (1996)]. Lifestyles and clothing were adapted as part of the survival and cultural responses to the local environment. Askar comes across many of the characteristics and advantages of previously practiced style of construction. Some of the rewards of the more traditional urban construction styles are highlighted below:

- Traditionally Kuwaiti local buildings, which include public, private and commercial types, used to be designed incorporating high thermal-mass which reduced the internal temperature fluctuations arising from diurnal-nocturnal ambient temperature-variations.

- Sizes and locations of the openings through the outer walls and roof were optimised with respect to the heat and light transfers through them, and for defensive reasons.

- Narrow streets can behave as cooling ducts by venting away hot dusty air. Increasing the wind-exposed surface areas of the external walls and other building elements enhanced the rate of heat loss via winds to the ambient environment; this can be seen in figure 3.15.

- The rates of heat transfer through the facades of buildings were reduced by employing low-thermal-conductivity building materials as well as designs that incorporated walls with cavities that acted as air ducts for heat-exchange purposes.

Mahgoub (2004), while trying to reflect the impact of globalisation on the built environment in Kuwait, states that the impact of globalisation on the built environment can be understood in relation to the aspects of globalisation. From the many aspects he highlights two of the major effects are mentioned here. The first states that building technology suggested new methods of construction and materials that require new methods of expression. The global marketplace liberated professional services and labour, building materials and construction methods, trade and investment from the limitations of national boundaries, this as the second aspect.

Below is an illustration of several pictures that reflects some of the highlighted points above. Looking at figure 3.15 below, it is obvious how close buildings used to be to one another (left); narrow passages between houses which make shadow from buildings fall on each other, reducing the effect of solar radiation on buildings figure 3.15 (right). Doors and window were not exposed directly to the sun light through the existence of shaded passages and overhangs, figure 3.16.

The replacement of the environmentally friendly old strategies with the new fashion in construction and building styles introduced the need for a more demanding building systems to provide comfort conditions for inhabitants to be accommodated. By arriving at such a turning point, the need for a large and growing electrical power supply industry was born.

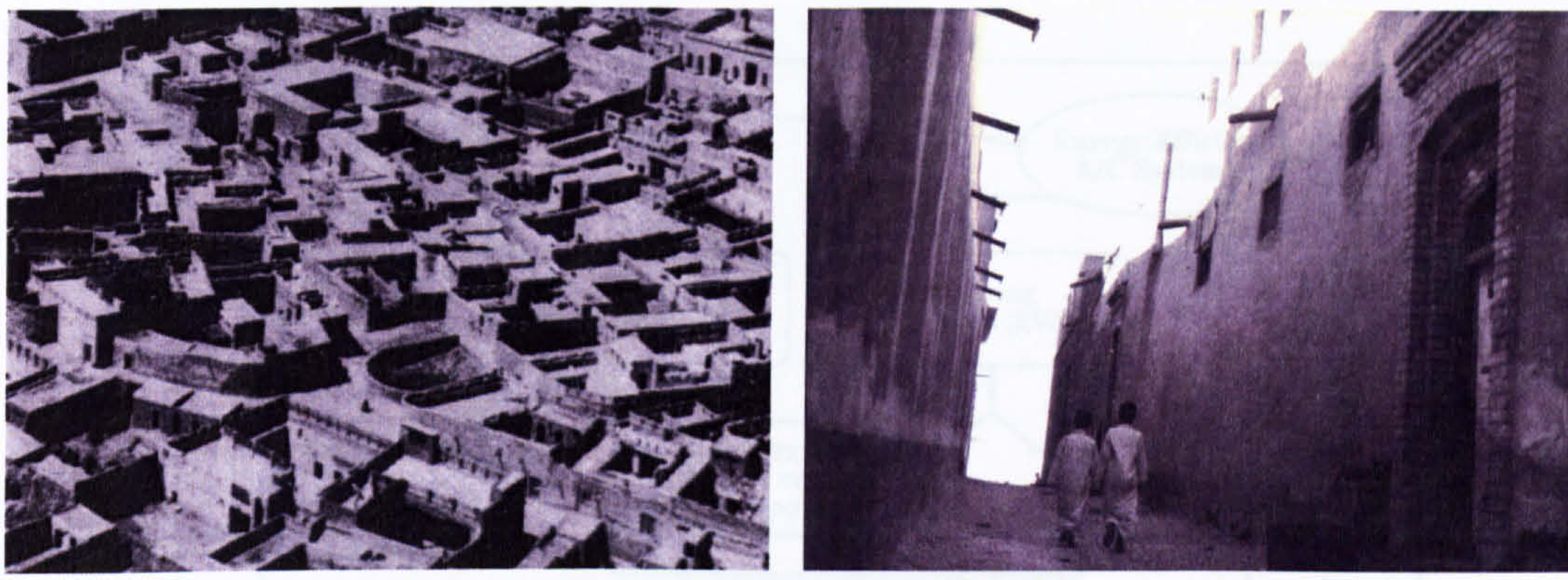

Figure 3.15 Picture from old Kuwait; layout of the city in the past (left) & a narrow street between houses

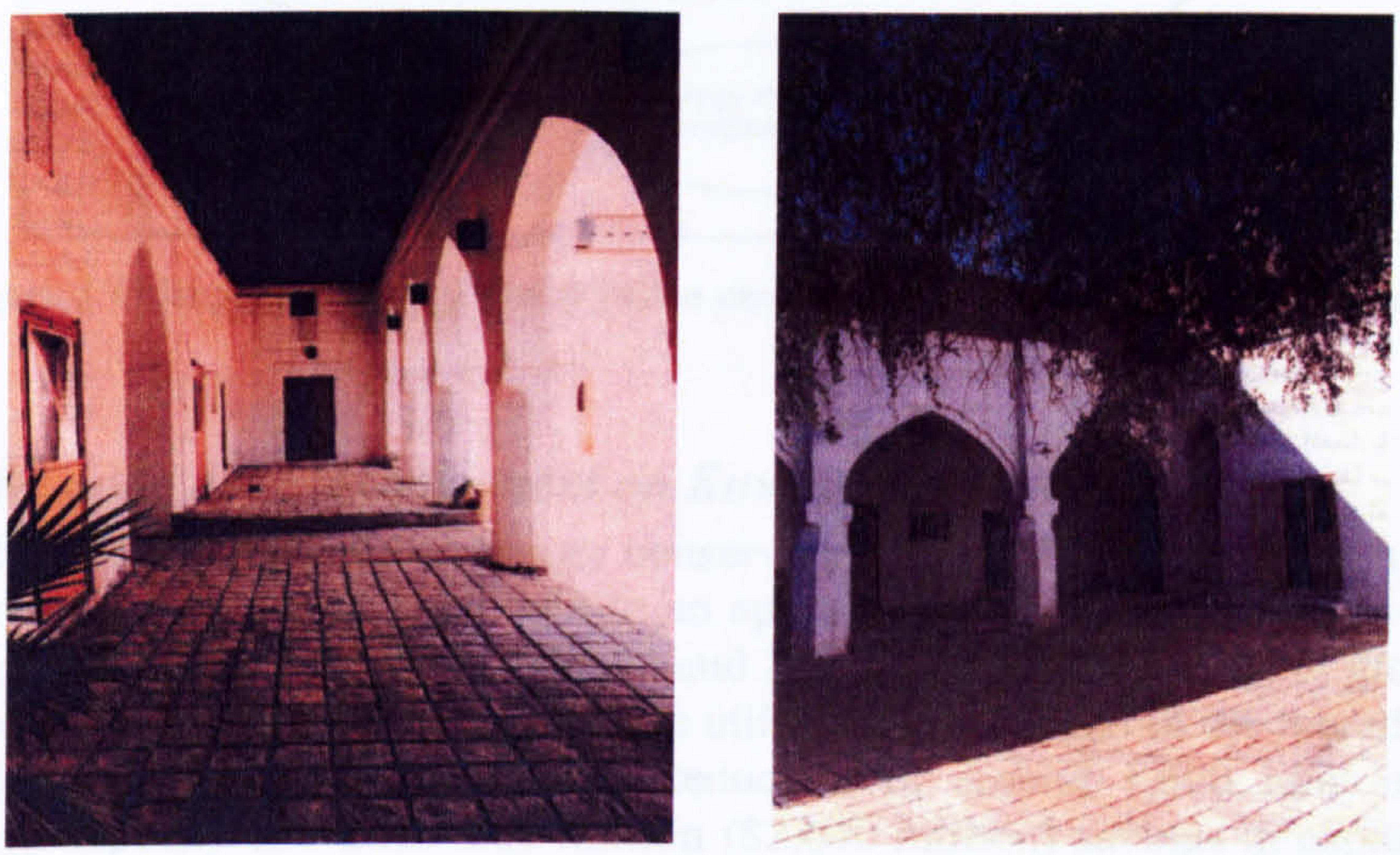

Figure 3.16 An old Kuwaiti house showing different strategies such as shading from trees, doors & windows are shaded so only daylight is allowed without the sun ray allowed inside

3.3 Energy and Power Management Measures

As mentioned earlier in this chapter, Kuwait introduced its first energy conservation code of practice in the early eighties (1983). This was an early attempt to reduce the amount of energy consumed in air-conditioned buildings. The impact of energy conservation measure would be in the form of introducing energy efficient buildings, energy efficient air-conditioning systems and the introduction of initial energy efficient operation strategies. Al-Marafie (1989), classifies the energy and power management techniques into three main categories:

1. Energy saving techniques
2. Power saving techniques
3. Combined energy and power saving techniques

Figure 3.17 demonstrates those impacts with the mutual links between all three.

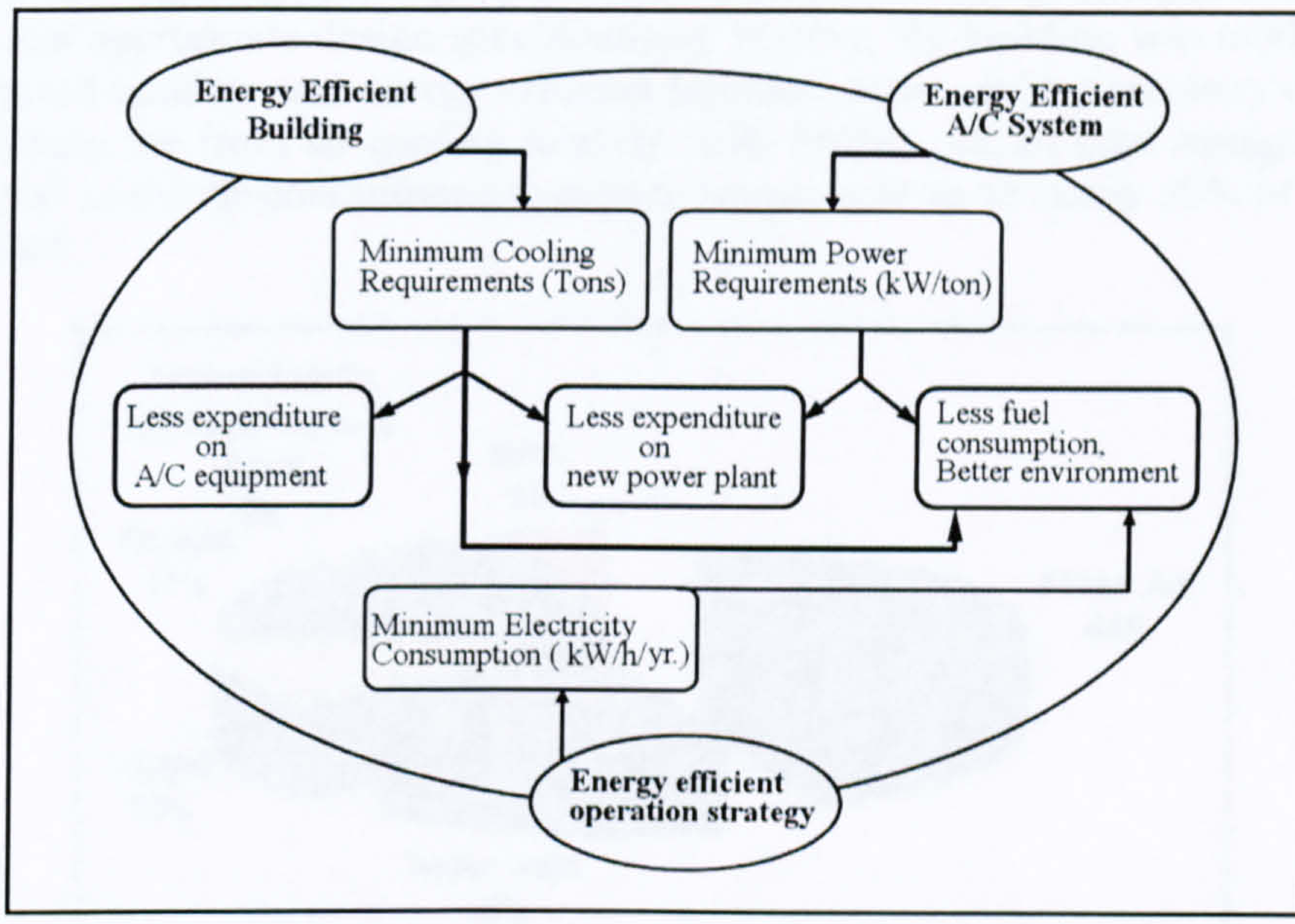

Figure 3.17 Impact of energy conservation measure on buildings level and national level

3.3.1 Demand Side Management on Kuwaiti National Level

The realizable potential of the energy conservation code of practice through adherence to the code was estimated to amount to an approximately 25% reduction in the annual rate of growth of the peak electrical load and 12% reduction in the rate of growth of the annual electrical energy production by the utility. The reduction in the rate of growth of the peak load would translate into a reduction of around 1,600 MW in installed generation capacity and a KD 800 million ($2,640 million) savings in capital costs by the turn of the century, Kellow 1989.

On the other hand, with the existence of the energy conservation code of practice in Kuwait, there were still many gaps left where improper practice in the built environment from an energy efficiency point of view existed. Different case studies which highlight the existence of such gaps justify the urgent need for DSM techniques to help make sure that the use of energy in large buildings is optimised with regard to national daily cycles of electrical power consumption. Two examples of applying energy saving techniques in Kuwait are described in the following section.

3.3.1.1 Energy Conservation Measures Applied on a New Construction

A two-storey speech and audio therapy clinic of 3000 m^2 was to be constructed in a hospital oriented area, Maheshwari, (1998-A). The original cooling load estimated by the consultant was 161.3 RT; a breakdown of the contributors to the load is presented in figure 3.18. In the initial design, the central air conditioning system was to have two air-cooled chillers of 90 RT capacities each, and an additional standby unit of the same capacity to meet the peak cooling demand.

However, the building cooling load was re-estimated using computer simulation software and appropriate design specifications. Further, the building was modified with double glazed window and energy efficient lighting. Also, cooling recovery units were used to reduce the fresh air cooling load by 50%. Finally, an ice cool storage unit was incorporated in the air-conditioning system to supplement up to nearly 50% of the peak-cooling load.

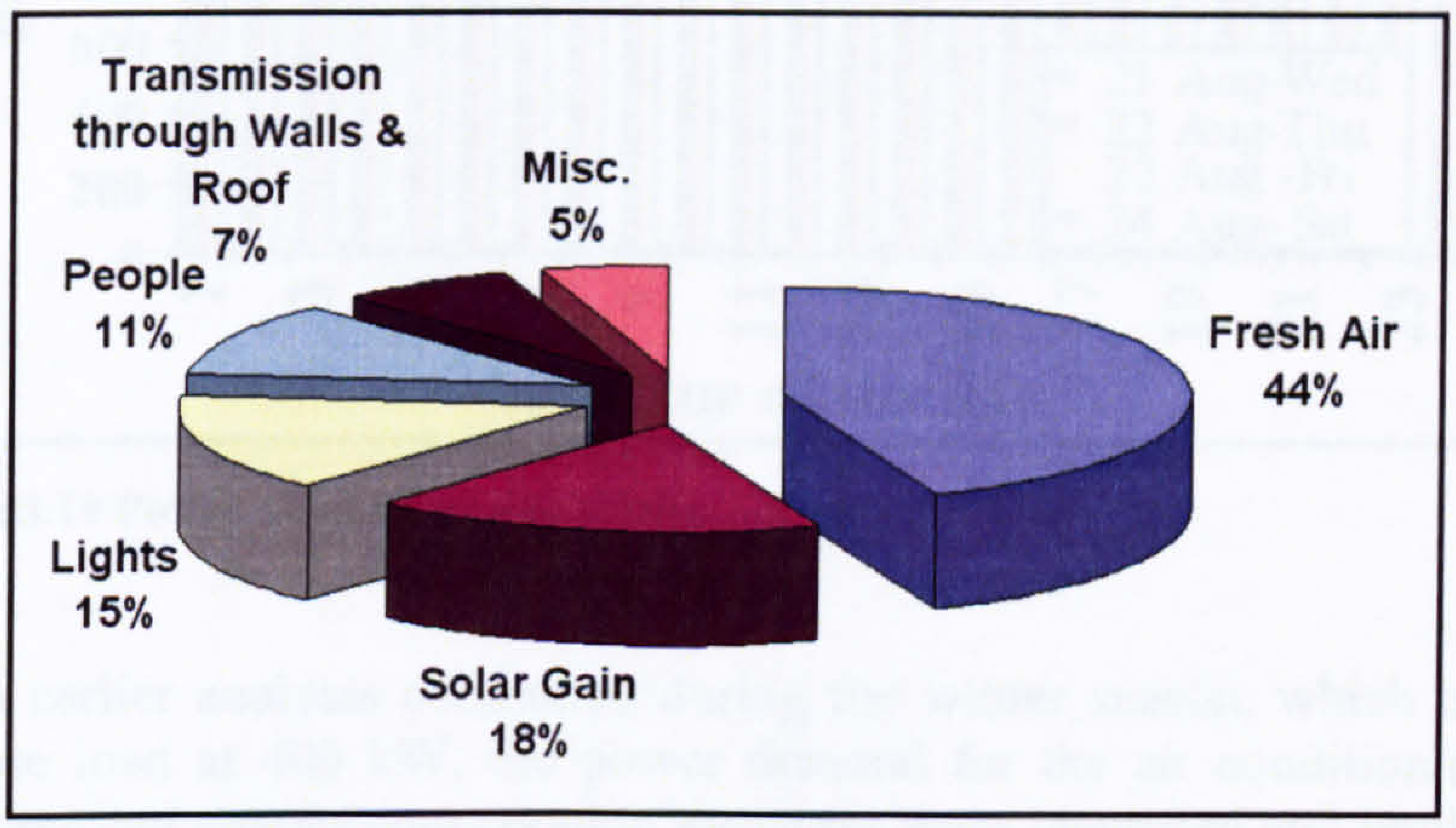

Figure 3.18 Cooling load distribution

The essential achievements for this project were through the following steps:

- Re-estimation of the cooling load using appropriate design specifications and a computer simulation program lowered the cooling load by 33.7%.
- Use of double glazed windows, energy efficient lighting hardware, such as electronic control, and energy recovery units reduced the building cooling load by 41.5%.
- Use of cool storage reduced the required cooling plant capacity by 50%. Such systems are recommended for buildings with part of day occupancy.

3.3.1.2 Energy Auditing in an Office Building

Kuwait Ports Authority (KPA) is an energy efficient structure that was built in 1990. Some of the important energy efficient features of this building are its well insulated walls and roof and coated glass airtight windows. A building automation system (BAS) was also installed to centrally control and monitor the operation of various components of the air-conditioning system. The annual electricity bill for KPA is approximately KD 12,000 ≈ $37,200. For a typical summer day, the total power demand of the KPA building was found to be 1500 kW, see Figure 3.19, irrespective of its occupancy and the diurnal fluctuations in the weather conditions.

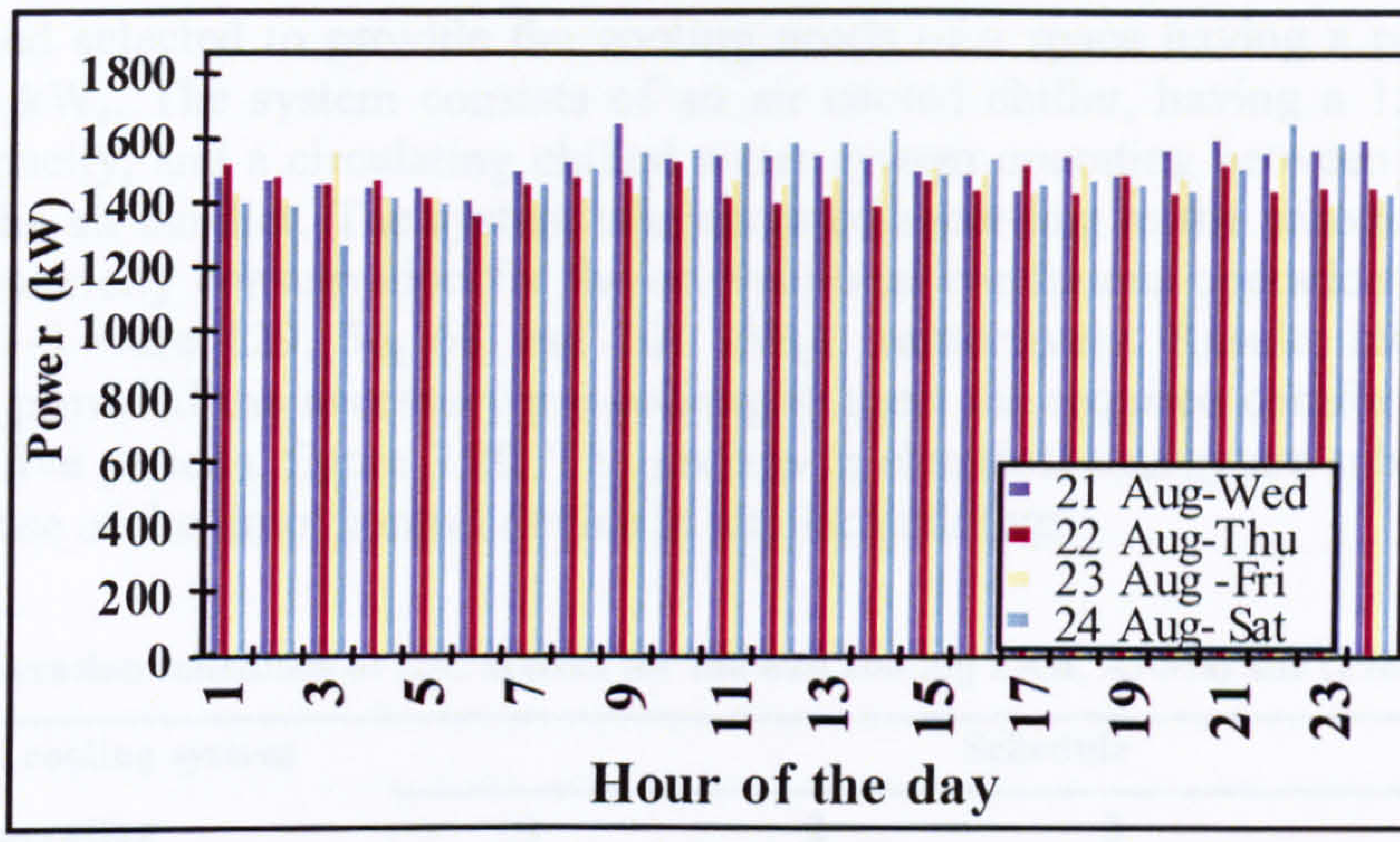

Figure 3.19 Power demand profile during summer

Based on an earlier analysis conducted during the winter season, which estimated the buildings base load at 400 kW, the power demand for the air conditioning system is 1100 kW. Important energy conservation measures were identified and implemented:

- Reduction in the number of lights in accordance with the lux level recommended by the MEW regulations
- Use of energy efficient compact fluorescent lamps in place of incandescent lamps
- Use of only one chilled water primary pump for one chiller in operation, mainly in lean periods of the summer season, and
- Reduction in energy consumption by the air distribution system by partially switching off the Air Handling Units (AHU) fans during non-occupancy periods of the building.

Yearly savings on the electricity bill of KPA are expected to be reduced by over KD 7000 ≈ \$21,700.

3.3.1.3 A Simple Control Strategy

Air-conditioning systems in Kuwait are normally operated on a 24 hours basis. However, irrespective of the type of building or time of day, controls can be used to provide comfortable conditions during the occupancy periods only. A test building was considered as a case study. It was occupied for five periods during the day, these were: (i) 03.30-04.00, (ii) 12.00-13.00, (iii) 15.15-16.00, (iv) 18.00-18.30, and (v) 20.00-21.00 hours of the day. To achieve acceptable comfort conditions during these periods, operation of the air-conditioning system was extended to provide for pre-cooling. Three sets of chiller operation schedules were chosen, along with the usual continuous operation for experimental simulation, table 3.1. The simulation experiment was designed and selected to provide the cooling needs of a space having a peak cooling load of 14 kW_c. The system consists of an air cooled chiller, having a 15 kW_c peak cooling capacity, and a circulating chilled water system operating between the cooling plant and the air handler. The system was operated according to the schedules of table 3.1. The electricity consumption for the conventional continuous operation and for the schedules 1-3 were 129, 56, 68 and 101 kW_eh, respectively. Results indicated that schedule 3 provided the necessary pre-cooling to meet the required comfort conditions during the five periods, figure 3.20. The savings in electrical energy are substantial and justify the use of the timer control device in similar buildings.

Table 3.1 Operation schedules of A/C system for the hall cooling need, Al-Marafie (1989)

Period of cooling system	Schedule			
operation	1	2	3	4
I	0200-0400	0100-0400	0100-0400	Continuous operation of the system
II	1000-1300	0900-1300	0730-1300	
III	1430-1600	1430-1600	1400-1600	
IV	1730-2100	1730-2100	1730-2100	
Total hours of daily operation	10	12	14	24

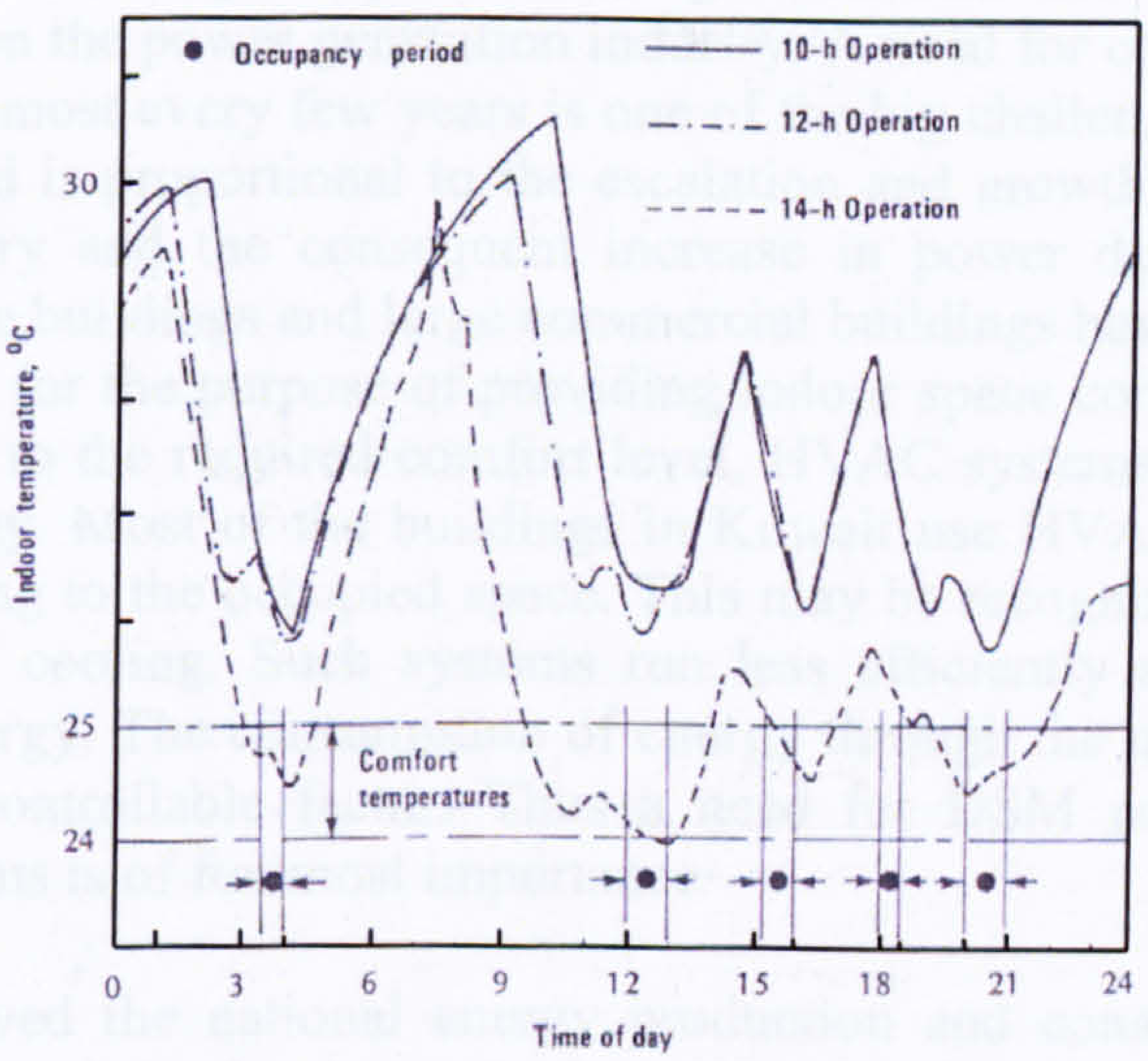

Figure 3.20 Indoor temperature variations for different schedules, Al-Marafie (1989)

The case studies introduced above, demonstrate the value of embracing DSM policies and that the need for energy efficient operation strategies is vital. Energy efficiency and large reductions in the energy demand were demonstrated through employing energy conservation measures in a new construction and in utilising different forms of energy management techniques in the other two existing facilities.

With the advancement of buildings technology and the improved integration of building environmental services for the application of more advanced and up to date techniques became due. Large potentials for energy efficiency improvements now exist as a result of the advancement in buildings services technology and DSM innovation.

3.4 Conclusions

Energy plays a critical role in modern societies. Many analysts believe that the costs of supplying and consuming energy have been increasing since the 1970s and that the world is embarked on a transition to costlier energy, as is pointed by Holdren (1992). Civilization is not running out of energy resources in any absolute sense, nor running out of technological options for transforming energy resources into forms our patterns of energy use require. What is running out, rather, is the capacity to expand energy supply at low cost – a capacity which was fundamental to the growth of material wealth in today's industrial nations and which had been the basis of expectations that today's less developed countries would be able to follow a similar path to prosperity, Xiannuan (1996). One way to cope with higher energy cost is energy efficiency. This can be achieved in part by introducing DSM strategies represented in the form of improved energy efficiency and reduction in the amount of energy consumed used for services provided.

Kuwait has and is witnessing growth of expansion in the economic, industrial and social aspects of modern life. A great and continual expansion in building construction and urban development is a major aspect of this growth. This has been accompanied by growing demands on the power generation industry. A need for constructing new power generation plants almost every few years is one of the big challenges that Kuwait has to confront. Such need is proportional to the escalation and growth in both the buildings construction industry and the consequent increase in power demand at the national level. Modern office buildings and large commercial buildings have to be equipped with large HVAC plants for the purpose of providing indoor space cooling to help bring the inside environment to the required comfort level. HVAC systems are one of the major consumers of energy. Most of the buildings in Kuwait use HVAC systems to provide instantaneous cooling to the occupied space. This may be recognized as a poor strategy to provide comfort cooling. Such systems run less efficiently and lead to a greater consumption of energy. The consumption of energy through the use of HVAC systems in buildings is a controllable factor. Thus a need for DSM policies for efficiently running those systems is of foremost importance.

This chapter reviewed the national energy production and consumption patterns for Kuwait. A rapid growth in the demand of energy over the past decades exists to the extent that it has been and remains an obvious significant burden on the nation's natural and economic resources. The situation indicates a clear and urgent need for the development of DSM strategies for the major consumers of energy, mainly air-conditioning systems in offices and large commercial buildings. Although energy conservation measures have been in action since 1983, yet, such measures need to be put into a proper DSM framework. In addition, efficiency measures must always be kept up to date as new building technologies are introduced. On the other hand, with the advancement in building services technologies in buildings, the need for developing effective and efficient energy strategies from a control point of view, turn out to be essential towards an improved and optimised DSM on national and local levels.

"Today the global energy industry finds itself in a bind. The International Energy Agency predicts that demand will rise by 30% over the next 25 years, but production is near capacity at present. Yet this is in a world where some two billion people do not yet have access to electricity" ... Floyd, Energy Resource Environmental & Sustainable Management

Chapter 4

Ice Thermal Storage as a DSM Strategy

4.1 Introduction

The objective of this thesis is to optimise the use of ice thermal storage as a DSM strategy in commercial and office buildings in hot arid countries such as Kuwait. This chapter aims to introduce an overall presentation of ice thermal storage, its basic concepts in brief and strategies that can be associated with it.

The common trend when designing a building is to assign an HVAC system that will be able to provide the rate of cooling required at peak periods and install controls to deal with lower cooling rates. This appears to be a logical approach and is adopted by many systems designers. However, designing for the worst condition can lead to inefficient systems unless care is taken when considering the requirements for smaller loads. The tendency for engineers to add-in a "margin of safety" when designing systems often leads to an oversized system with much higher capacity than that actually required, which can lead to even lower efficiencies for part load operations.

While a strategy to provide sufficient plant cooling capacity to deal with instantaneous demand is valid, in the context of Kuwait, and probably many other countries, this will lead to the need to building new power plants in order to have sufficient installed capacity to cover the instantaneous demand.

Demand side management utilises energy storage devices or alternative energy sources to change the electrical energy usage profile by shifting loads to other periods of the day, Francis (1999). This helps power utilities to maximise the use of generating plant and the efficiency of electricity generation by managing demand away from existing times of peak demand to other periods when spare electricity generation capacity is available. To promote and encourage customers to adopt load management strategies that reduce utility demand peaks, utility companies in countries such as the United States and the United Kingdom, and public utilities as in France, utilise tariff schemes that represent different charging regimes for on-peak and off-peak periods. End users are encouraged to transfer electrical load to periods when the lower priced off-peak tariff rates operate and to store energy, for use during periods when the tariff prices are higher. In this way, the end user is able to achieve savings by utilising the off-peak tariffs. Because of the incentives provided by the varying rate structure, cool storage technology has re-emerged in the USA as a cost effective load management measure for space cooling, Hasnain (1998). Cool storage is considered as a useful electricity demand-side management technique for application in buildings.

Thermal Energy Storage (TES) now is a common practice in many countries. TES used for both heating and cooling purposes is considered as an economic strategy that can be associated with HVAC systems in buildings. For countries such as Kuwait where the cooling load comprises a big share of both the annual peak load and the total yearly electricity consumption it is a valuable technique. However, the use of cool storage is not yet a common practice in Kuwait.

In Kuwait the Ministry of Electricity and Water (MEW) does not employ a commercial charging scheme but charges the end user a price that is equivalent to only 11% of the generation and supply cost. Consequently, the end users display little interest in managing their demand. However, from a national viewpoint this situation is of little benefit. The development of electricity power demand management strategies will become increasingly important as the summer peak continues to expand beyond current generating capacity. Additionally, if at some stage in the future the Kuwait power sector is to be privatised then new and more commercially viable charging schemes are likely to be introduced.

4.2 Thermal Storage Systems

One strategy to allow reduced plant capacity and consequently more efficient operation is to utilise ice storage during periods of peak demand. When air conditioning constitutes a major proportion of summer peak loads, the potential technical and economical benefits for the exploitation of cool thermal storage can be considered. Cool thermal storage technology has advanced in the past few years to provide energy and environmental conservation and electrical load shifting benefits.

Generally speaking, cooling systems incorporating cool storage have distinct size and capacity advantage over conventional air conditioning systems in office and large buildings. When a new system is to be invested in a new building, utilising cool storage allows the installation of cooling plant with much reduced capacity. A balance can be achieved between the reduced cost of the cooling plant and the additional cost of the ice store and the prospect of reduced running costs through improved efficiency. In the case of an existing building, where the load has increased due to a change of use, instead of installing new chillers that will cope with the load during periods of peak consumption, it is probably more energy efficient and cost effective to install a cool storage system to assist the existing cooling plant. Figure 2.1 shows a complete circuit of an HVAC plant incorporating an ice thermal storage within the system.

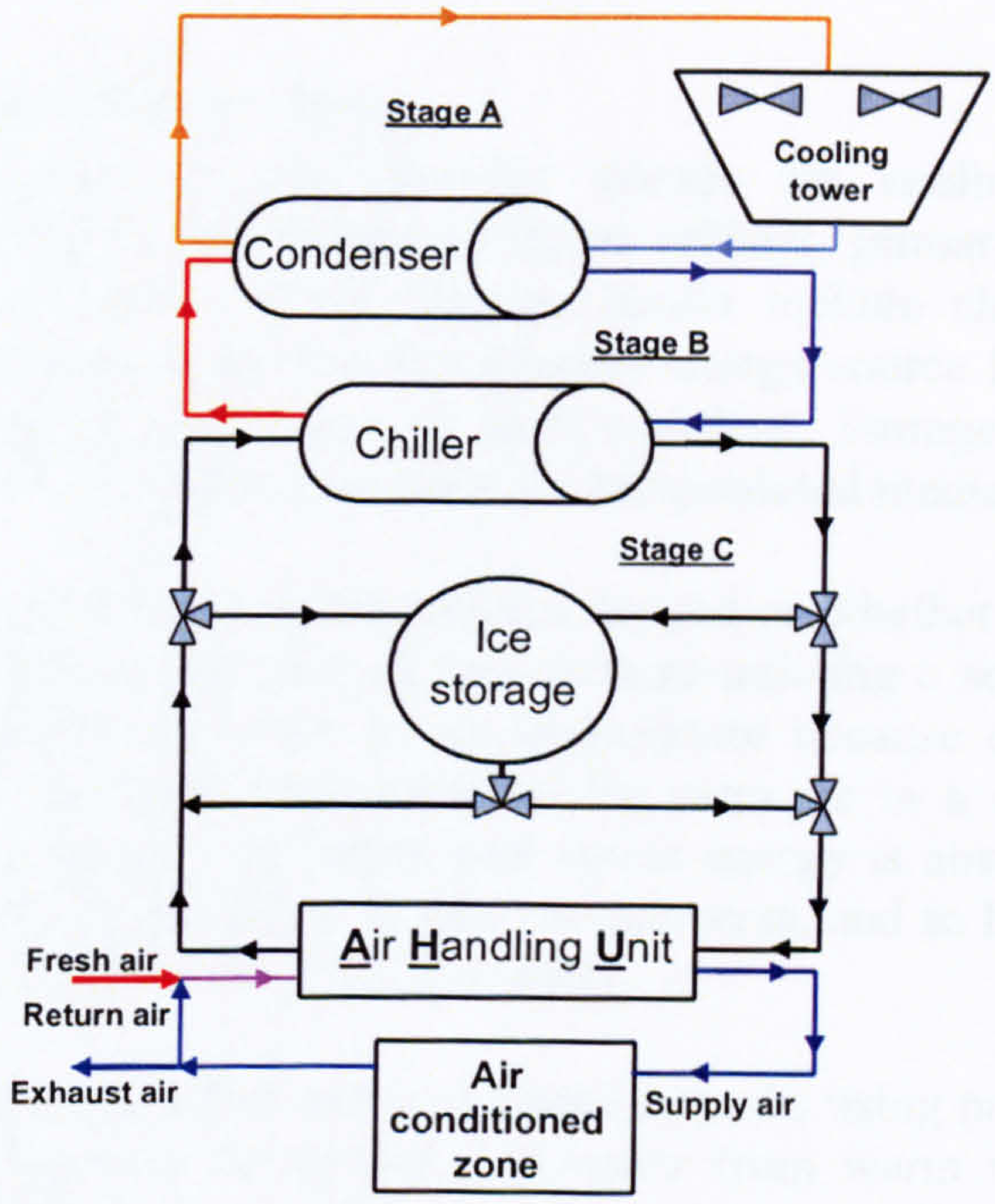

Figure 4.1 An HVAC plant circuit with an ice thermal storage incorporqated within

In Kuwait the cooling of buildings comprises 61% of the summer electrical demand. Referring back to figure 3.3 in the preceding chapter, it can be seen that building cooling and air conditioning incur a peak electric demand during summer period. On a daily load cycle basis, the peak load occurs only for few hours, which makes cool thermal storage a favourable candidate for altering the electrical usage pattern. It permits such a shift by decoupling chiller operation from instantaneous loads. A cool storage system meets the same total cooling load in a given period as a non-storage system but with a smaller instantaneous cooling capacity.

As regards electricity generation, thermal energy storage is known to conserve energy at the source of generation. McCannon (1995) defines a new aspect of thermal energy storage known as "source energy conservation". It is well documented that electricity transmission and distribution losses are significantly lessened at night because of lower ambient temperatures and reduced electricity demands, McCannon. The source energy and transmission and distribution savings are realised only by technologies such as thermal storage that use electricity generated and distributed at night. When added to site energy savings of storage, the net total reduction in fuel use and emission from use of thermal energy storage can be considerable.

The electricity generation sources that meet a peak load supply are generally less efficient than those that meet the base load. In some cases the relative generation efficiency of the top-up sources is as low as 65% of efficiency of the base load source. The efficiency of ice storage is around 85% to 90% greater relative to producing chilled water at 5°C. Under these circumstances ice storage conserves energy, McCannon (1995).

4.2.1 Cool Thermal Storage Types

The possible approaches to cool thermal storage for cooling buildings can be characterised according to the storage medium utilised, primary energy source, and storage technology, Dorgan (1994). Storage media include chilled water, ice, and eutectic salt phase change materials. The primary energy source for generating cooling can be electricity, natural gas, steam, or recovered heat. Storage technologies include chilled water tanks, ice harvesting, ice-on-coil, encapsulated media, and slurry systems.

The heat transfer characteristics of the systems depend on whether sensible and/or latent heat transfers dominate. In the case of cool storage utilising a sensible heat store, the storage medium experiences a rise in its temperature because of the heat exchange between the hot and the cold fluid streams, for example in a chilled water storage system. On the other hand, with latent heat stores energy is absorbed during a phase transition from solid to liquid, liquid to gas, or vice versa, and so heat transfer occurs at or close to a constant temperature, CIBSE (1994).

For chilled water systems, chilled water is stored in tanks using natural stratification or other techniques to separate the stored cold water from warm return water. Chilled water uses the sensible heat capacity of water to store cooling. Those systems are typically charged at temperatures between 4 and 7 °C. This temperature range is compatible with most non-storage cooling systems and allows the use of conventional chillers. The storage volume depends on the temperature difference between the water supplied from storage and the return water and the degree of separation between warm and cold water in the storage tank. A temperature difference of 11 °C is the practical maximum for many building cooling applications. The practical minimum storage volume for chilled water is approximately 0.086 m^3/kWh of load at an 11°C temperature difference , Dorgan (1994).

A latent heat storage system uses the latent heat of fusion of water or other phase change materials. The storage volume depends on the final proportion of ice to water in a fully charged tank and is generally in the range of 0.02 to 0.03 m^3/kWh of load, depending on the specific ice storage technology. To store at the temperature of ice requires refrigeration equipment that provides charging fluids at temperatures below the normal operating range of conventional air conditioning equipment. Refrigeration equipment must provide charging at temperatures of -9 to -3 °C. Special ice making equipment or standard chillers modified for low temperature application are used. The heat transfer fluid for ice making may be a refrigerant or a secondary coolant, such as glycol, brine or some other antifreeze solution.

Several cool storage technologies use ice as the storage medium. Ice-on-coil systems can be classified into two main classes. The first class is known as *direct* refrigeration ice storage system, while the second class is described as *indirect* refrigeration ice storage system. Direct ice storage is characterised by production of ice directly on the evaporator and includes the ice harvester. It consists of serpentine coil submerged in an insulated open tank of water. The inside of the serpentine coil is essentially the evaporator coil of the refrigeration circuit. Ice is built up on the outside of the coil. In this system, the evaporator of the chiller and the ice storage tank are a single unit. Indirect ice storage is characterised by the production of ice at a remote location and includes ice container systems and ice-on-coil internal melt system, Strand (1994). In such systems, a brine solution is circulated between a chiller and the ice storage unit. The chiller and the storage unit are considered to be independent from each other and are handled separately.

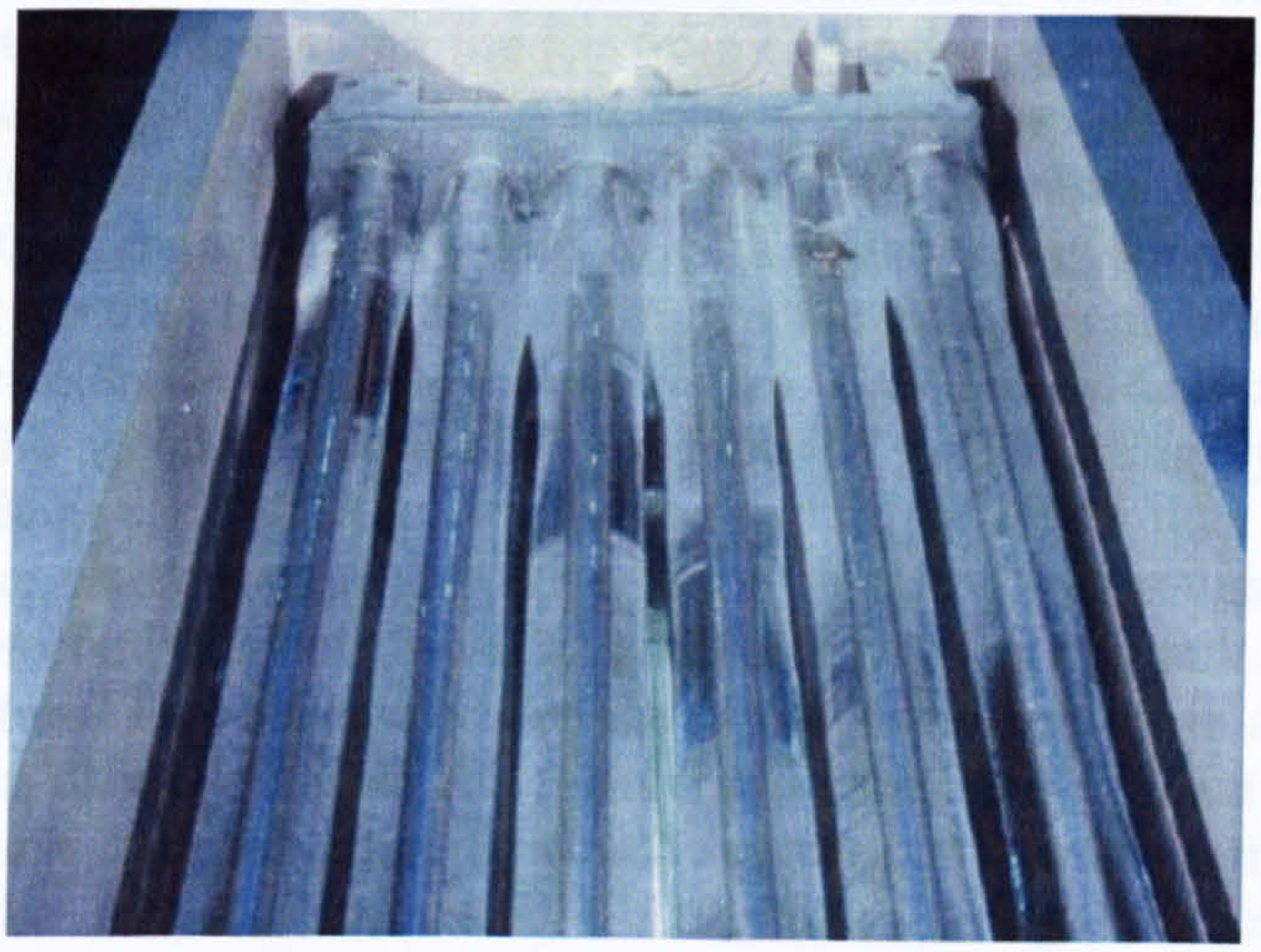

Figure 4.2 External melt ice-on-coil system with ice formed on pipe coils

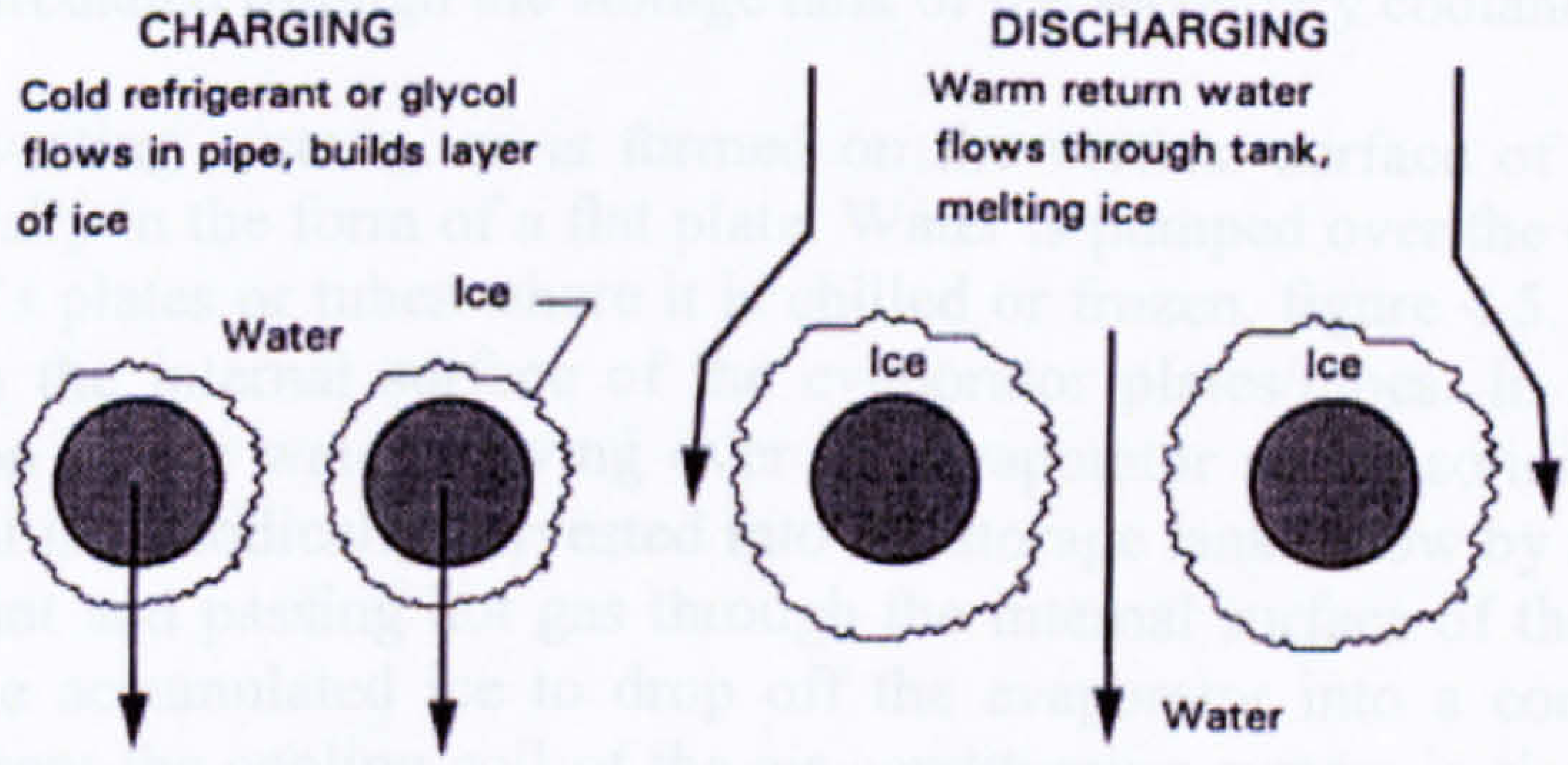

Figure 4.3 External melt ice-on-coil

The external melt ice-on-coil is also known as ice builder. Ice is formed on submerged pipes or tubes, which act as a simple heat exchanger. Refrigerant or a secondary fluid is circulated through the submerged pipes at a temperature below 0°C. Ice is built and stored on the exterior surface of the heat exchanger coil submerged in a non-pressurised water tank, figure 4.2. The storage is discharged by melting the ice from the outside. This is achieved by circulating the return water of the air conditioning system through the tank. The stored ice melts and the water becomes chilled. Figure 4.3 shows the charging/discharging process. For this type of system, the tank is considered fully charged when the ice built around the pipes reaches a determined thickness. Ice is normally built to a thickness of 40 to 60 mm on the pipes, depending on the application. Care must be taken to avoid overcharging the system as this might result in bridging between adjacent tubes. This will make it difficult to discharge as the ice bridges obstruct water flow and ice melting, resulting in higher discharge temperatures.

With both the internal melt ice-on-coil and the external melt system, ice is formed on submerged pipes or tubes. The heat transfer fluid is circulated through the pipes at a temperature below $0^{o}C$ during the ice-building phase of operation. However, in the internal melt system cooling is discharged by circulating either water or secondary coolant through the pipes, melting the ice from the inside, see Figure 4.4. This has an advantage that during partial refreezing the heat transfer does not occur across a width of partially melted ice. The cold secondary coolant is pumped through the building cooling system. Chillers are usually used to chill water that is supplied to the building air handling unit by the chilled water pump. On the other hand, when arrangement is made to incorporate an ice thermal storage system, a secondary coolant circuit is added to the system. The secondary coolant is used during the charging cycle to freeze the water in the tank as it is able to achieve temperatures lower than $0^{o}C$. During the discharging cycle, water can be chilled either by passing it through the ice store or alternatively the secondary coolant can be circulated through the tank and cooled to the required temperature. This all depends on the HVAC arrangement in a building. Figure 2.1, shown earlier, displays the HVAC refrigeration and cooling plant with an ice store integrated with the system. In stage B, which represents the main refrigeration plant, a refrigerant is used as in a conventional HVAC system, chilling the water that goes to the air handler. In stage C, when a conventional system with no ice storage is used, then chilled water coming from the chiller goes directly to the load. Alternatively, when ice storage is incorporated with the system both the refrigeration plant and additionally water can be circulated through the storage tank or the secondary coolant is circulated.

In the ice harvesting system, ice is formed on the vertical surface of the evaporator, which is generally in the form of a flat plate. Water is pumped over the outer surface of the evaporator's plates or tubes where it is chilled or frozen, figure 4.5. The refrigerant passes through the internal surface of the evaporator plates/tubes. In the ice making mode, a portion of the water flowing over the evaporator plates solidifies, forming a layer of ice that is periodically harvested into the storage tank below by interrupting the liquid refrigerant and passing hot gas through the internal surface of the plate or tube. This causes the accumulated ice to drop off the evaporator into a containment tank. Return water from the cooling coil of the air-conditioning system is circulated through the ice tank then pumped from the tank to the cooling coil to meet the air-conditioning cooling load.

Encapsulated ice storage consists of water or water-based solutions contained inside submerged plastic spheres. During the charging cycle subfreezing temperature coolant from a chiller is circulated through the storage tank and past the plastic containers, freezing the water or solution within them. Thawing occurs as cold or warm coolant is circulated through the tank holding the containers. Both processes are shown in figure 4.6.

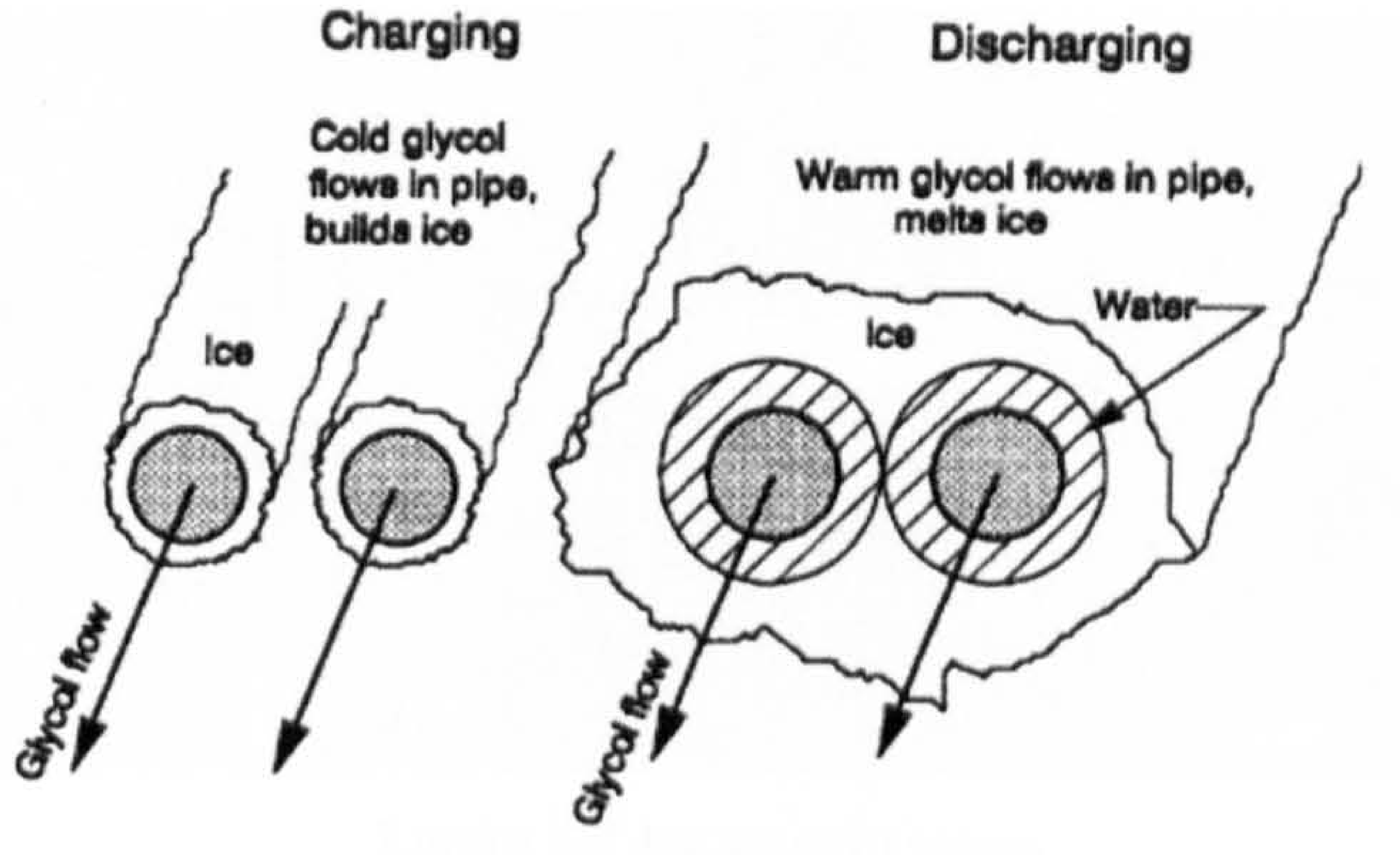

Figure 4.4 Internal melt ice-on-coil

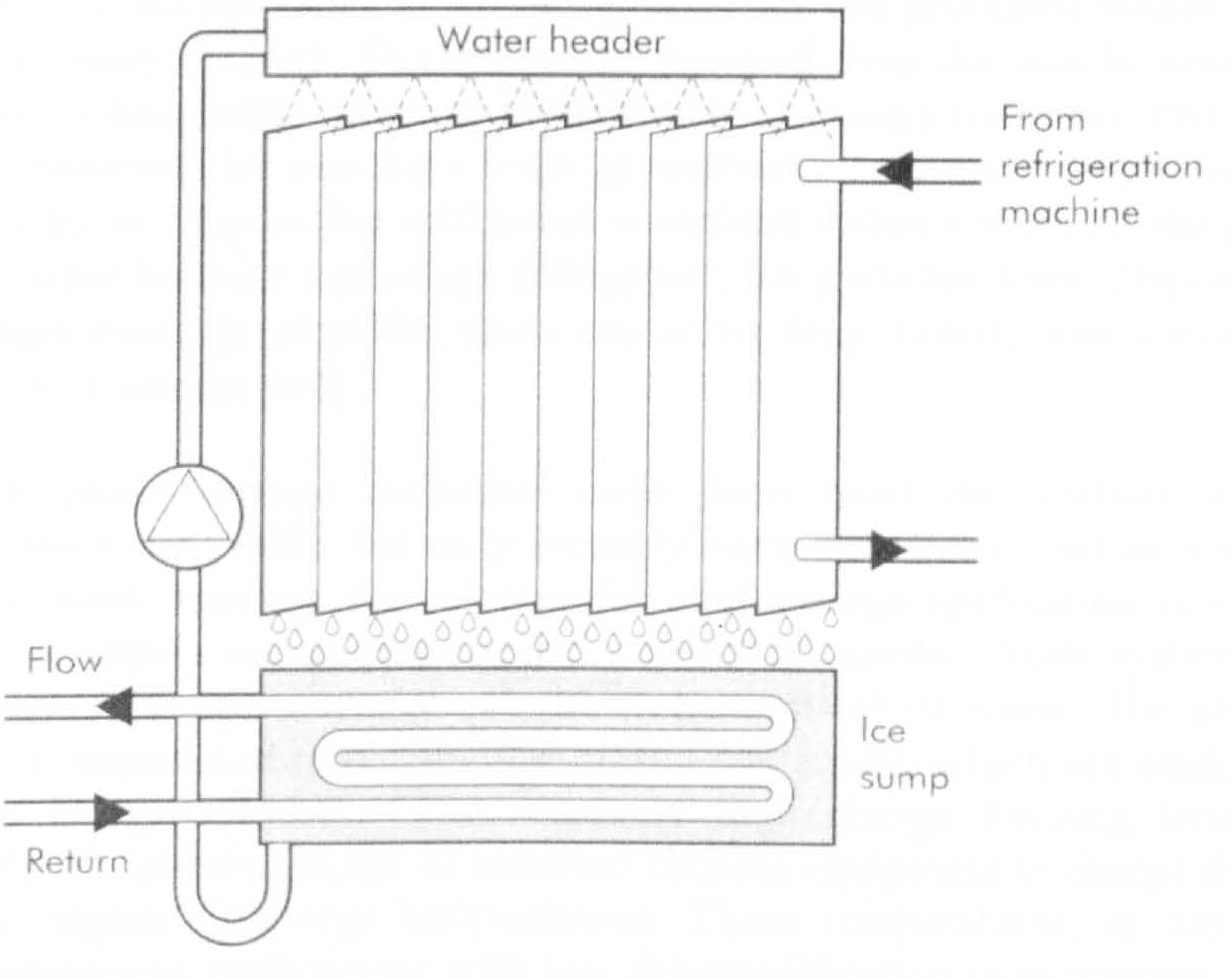

Figure 4.5 Ice harvesting system, [21]

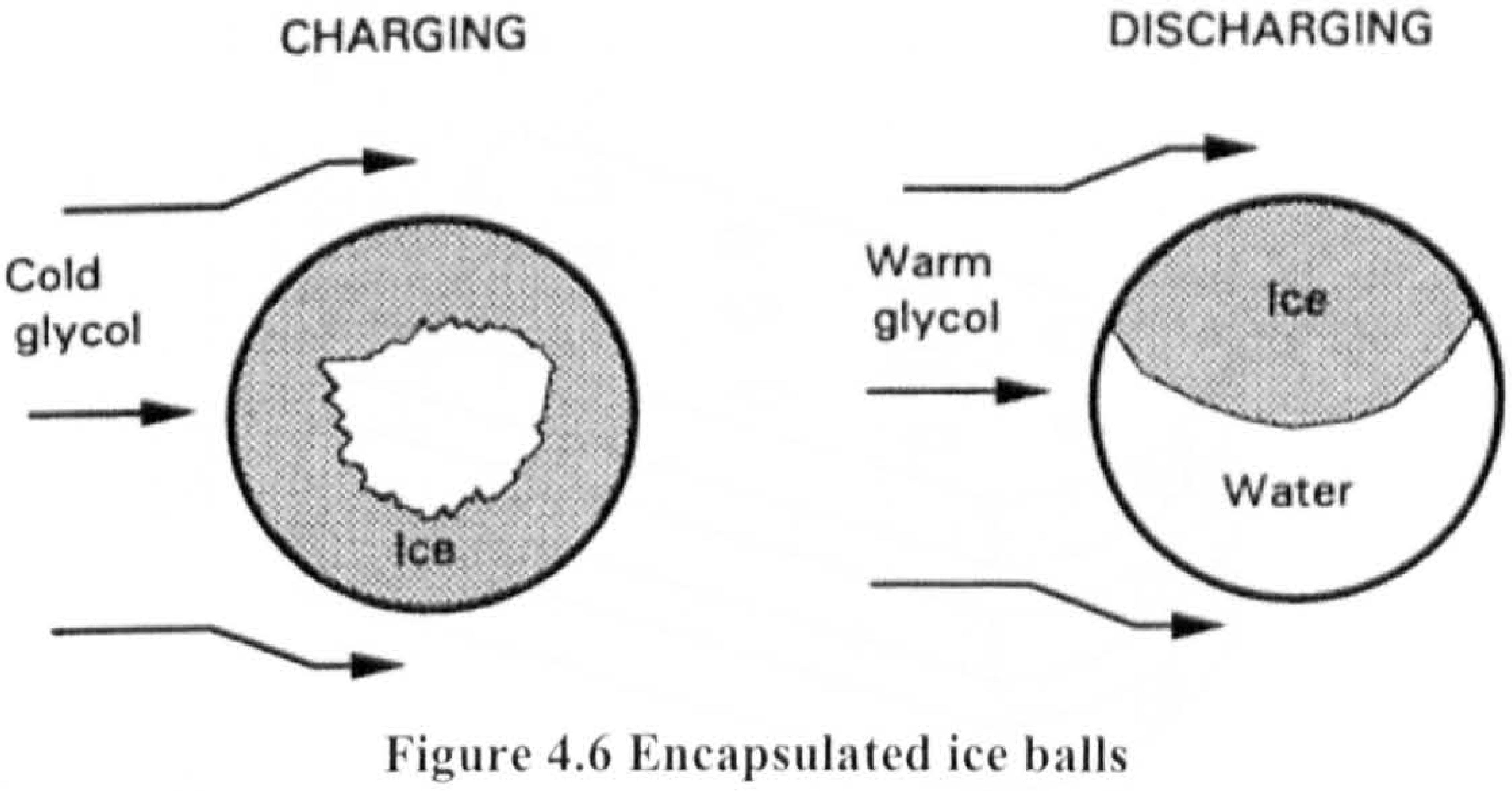

Figure 4.6 Encapsulated ice balls

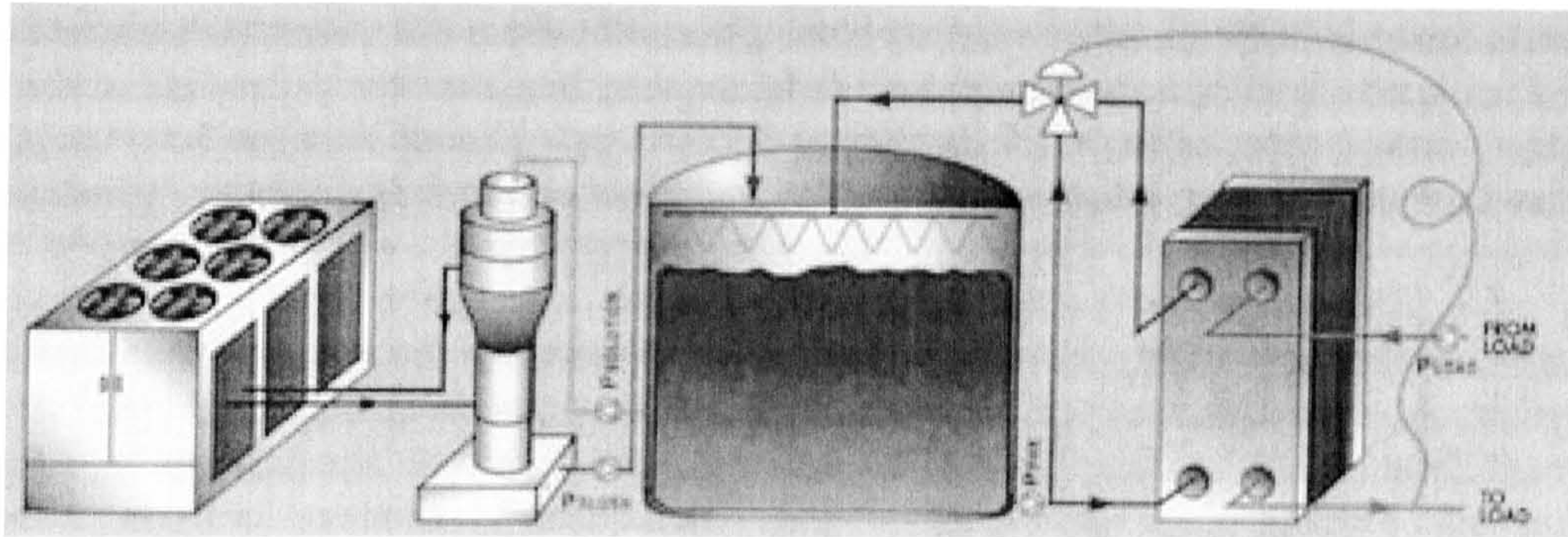

Figure 4.7 Ice slurry system

In the ice slurry system, figure 4.7, water in a water/glycol solution is frozen into slurry and pumped to a storage tank. Small particles of ice are produced within the solution resulting in a slushy mixture. Slurries can be pumped from the tank to heat exchangers or directly to cooling coils, resulting in high rates of energy transport, PNL (2000). Ice particles are generated by passing a weak glycol/water solution through the tubing that is surrounded by an evaporating refrigerant contained within a shell. As the glycol/water solution is cooled by the evaporating refrigerant, ice particles form. Depending on the system configuration, the resulting slush can either drop directly into a storage tank or be pumped into a storage tank.

Eutectic salt phase change materials have been used for various heat storage applications since the 1800s, but only recently have they been used as a cool storage medium. The most common formulation for cool storage application is a mixture of inorganic salts, water, and nucleating and stabilising agents. Such systems generally melt and freeze at temperatures above the freezing point of water. The phase change materials are encapsulated in rectangular plastic containers, which are stacked within a storage tank, Dorgan (1994). The relatively high charge freezing temperature of approximately 8°C allows the use of standard chilling equipment to charge the store, but also leads to higher discharge temperatures. These temperatures, in turn, limit the operating strategies to applications with low dehumidification requirements. Figure 4.8 shows a stack of containers. Water serves as the heat transfer fluid; it circulates through the storage tank among the eutectic salt containers, carrying heat to or from the storage medium.

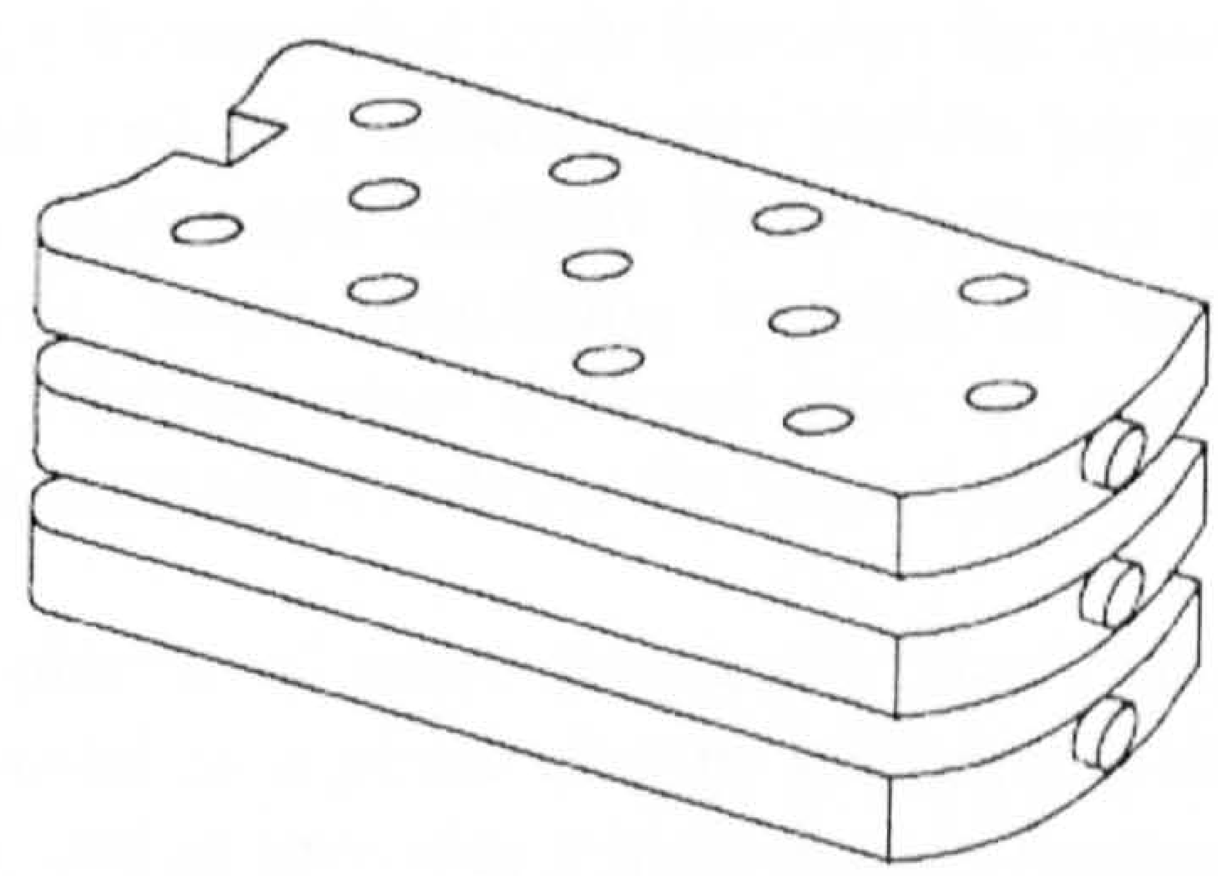

Figure 4.8 Eutectic salt containers

Steel and concrete are the most commonly used types of tanks for chilled water storage. Most ice harvesting systems and encapsulated ice systems use site-built concrete, while external melt systems usually use concrete or steel tanks, internal melt systems usually use plastic or steel, and concrete tanks with polyurethane liners are common for eutectic salt systems, FPL.

Internal melt ice-on-coil systems are the most commonly used type of ice storage technology in commercial applications. External melt systems are more common in industrial applications, although they can also be applied in commercial buildings and district cooling systems. Encapsulated ice systems are also suitable for many commercial applications. Ice slurry systems have not been widely used in commercial applications, Perekhodtsev (2002).

4.2.1.1 Relative merits of different storage media

Three types of storage medium have been identified; chilled water, ice and eutectic salts. Chilled water and ice are more common as storage media because eutectic salt mixtures have some limitations.

Chilled water systems use conventional water chillers, operating under the same general conditions for storage as for the conventional air conditioning system that they support. This provides the opportunity to maintain the original refrigeration design without the need to modify the piping or air handling equipment that is already in use. In places where chilled water storage systems are used, the same storage tanks can be utilised to serve as reservoirs for fire protection.

Hasnain (1998), made a brief comparison between chilled water and ice storage systems. Although chilled water systems appear to be relatively simple in terms of both design and operation, they have proved much more difficulty in practice than in theory. The first problem is storage volume. Each cubic meter of chilled water can provide only 1.16 kWh of cooling for each degree of temperature rise that the chilled water in the store experiences. Therefore, the volume requirements for chilled water storage are very large and this tends to discourage its use. The second design consideration in chilled water systems is the need to separate the cold water from the warm return water. Various methods have been employed to maintain separation between the stored supply and the warmer return water. The most common method is to use stratification in the storage tanks to achieve the necessary separation between the cold and warm water by creating and maintaining a thermocline layer between the warm upper zone and the cool lower zone. However, the cost of a chilled water system per gallon of capacity declines as the size of the tank increases. Chilled water systems are most economical for applications with cooling loads requiring storage of more than 7000 kWh or approximately 6000 m^3. Chilled water systems have an economic advantage in large systems, where space can be made available for large capacity tanks.

Ice storage systems are now used more frequently than chilled water systems. In ice storage system, water is used as a phase change medium to utilise the advantage of its high latent heat of fusion, which provides a high density storage capacity and so reduces the volume of the storage vessel. The latent heat of fusion energy storage concept, which involves storing and recovering heat through the solid-liquid phase change process, has two distinct advantages, Dincer (2002). First, the latent heat of most materials is much higher than their sensible heat, thus requiring a smaller mass of storage medium for storing/recovering a given quantity of thermal energy. Second, the thermal storage process occurs at a nearly constant temperature, which is desirable for the efficient operation of most thermal systems. Hasnain (1998) lists the advantages of ice thermal storage systems over chilled water storage systems as follows:

- Larger cooling capacity for a given storage volume
- Less space requirement, for both retrofits and for new constructions
- Less thermal losses to the surrounding environment, owning to smaller surface area.
- Fewer design restrictions, for example, elimination of stratification requirement within the storage tank.
- Lower cost of maintenance and water treatment.
- Lower storage temperature, reducing the cost of pumping and air distribution.

When an air conditioning system has ice storage integrated with it, a two-stage operation cycle exists. First the charging cycle, figure 4.9-A, takes place, where one chiller or more starts to operate for ice freezing. At this stage, the chiller is considered to be in direct communication with the ice storage. During normal periods the chiller would work as normal and provide the cooling required directly to the air-handling unit. The discharging cycle, figure 4.9-B, which is the second phase, takes place at a time where the load demand starts increasing. This usually happens at about midday, when the need for a larger system cooling output occurs. With a conventional air conditioning system, a second chiller might begin operating at this time to help provide sufficient cooling capacity for the increased demand. This would lead to a higher consumption of the energy utility at that time. However, with the existence of the ice storage, circulation of the cooling medium inside the storage begins while the chiller continues to work at full load, allowing the plant to be operating at its optimum efficiency.

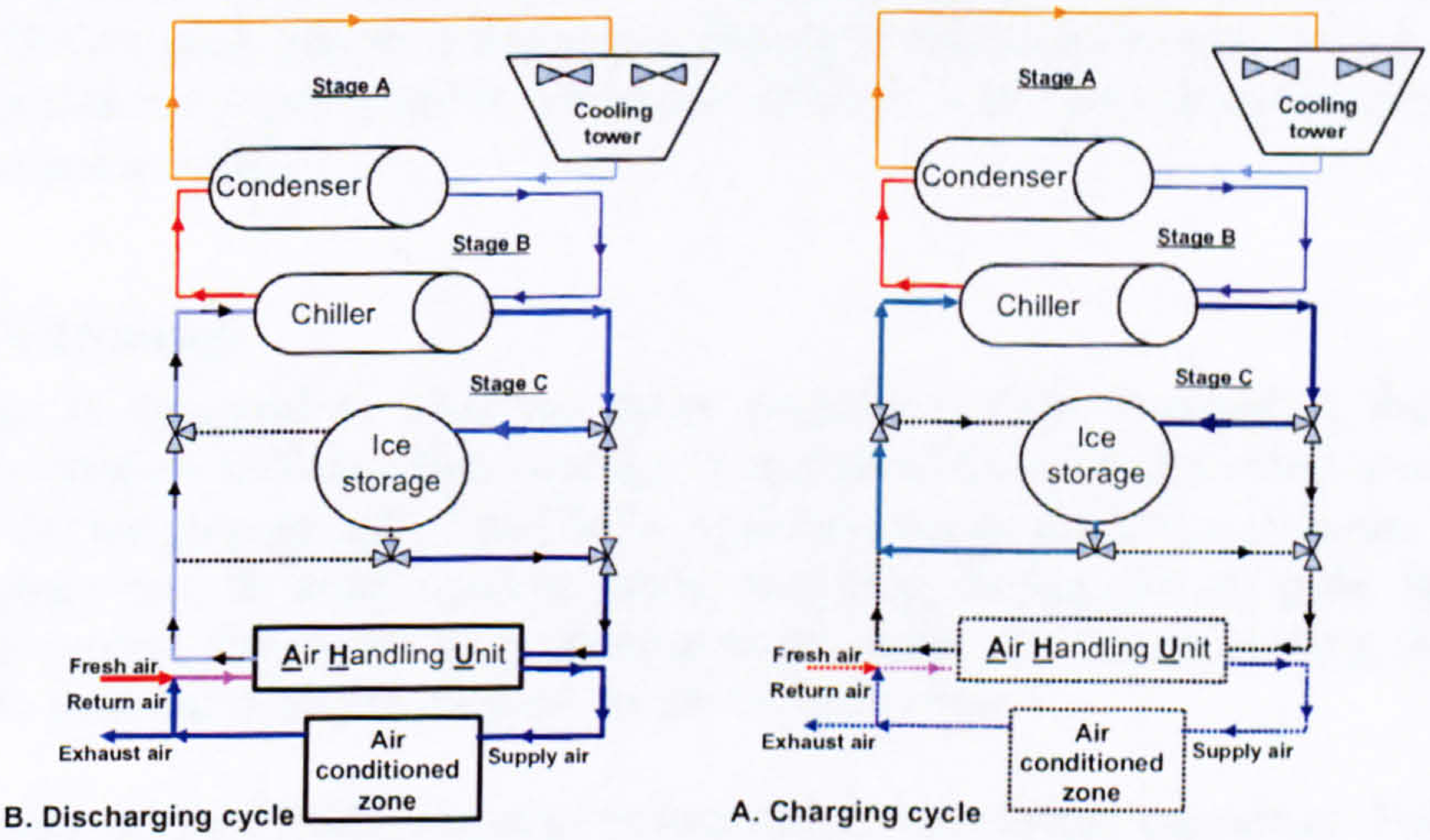

Figure 4.9 Charging and discharging cycles for ice storage system

Regarding the conditions that must exist in order to make ice storage an economically attractive approach, it is important to mention the merits that would accrue from such a system as:

- Reduction in the refrigeration plant capacity.
- Chiller plant will work mostly at 100% capacity and as a result it will work close to optimum efficiency.
- Peak demand shaving.
- Environmental benefits.
- More economic operation

Ice storage systems have very low standby losses. Thermal losses in CALMAC ice tanks are less than 1% per day at 27°C ambient temperature. If the entire surface of the tank were to rise to 55°C, standby losses still would be less than 2%, (Calmac).

For the purpose of this research work, internal melt ice-on-coil storage system was chosen as the technology to be utilised for the investigation to be conducted throughout the project. The reasons for this relate to the modularity and predictive control strategies of the system it is intended to apply to office buildings. As such buildings have limited space; an ice storage system becomes a better candidate than a chilled water system that requires a larger storage volume. Ice storage technology is a better nominee for the investigation and examination of the implemented modularisation of the storage system. Additionally, internal melt ice-on-coil ice storage systems are most commonly used in office buildings and commercial sector.

4.2.2 Ice Storage Systems Operation Strategies

Operation strategies for ice storage systems can be placed into two main categories, full and partial storage systems. This refers to the proportion of cooling load that is transferred from on-peak periods to the off-peak charging period used to replenish the ice store. The on-peak period is the period during which high demand occurs and might attract high electricity price tariffs, while the off-peak is the period that has low demand and a lower price tariff.

4.2.2.1 Full Storage

Full storage is designed to shift the entire on-peak cooling demand to the off-peak hours. The system utilising this strategy is designed to meet the entire peak-cooling load from the ice storage unit. The chiller operates during the off-peak hours to charge the ice storage and to meet cooling loads occurring during the off-peak times. The storage will reserve the entire daily cooling requirement at night, providing the shifting of the entire demand from the on-peak to the off-peak time.

Such a system requires relatively large refrigeration and storage capacities. Full Storage operation is most attractive where a high on-peak demand charge applies and the on-peak period is relatively short. With use of the full storage strategy, the peak cooling electric demand could be reduced by 80 – 90 % compared with a conventional cooling system. Figure 4.10 shows the full storage strategy, Hasnain (1998).

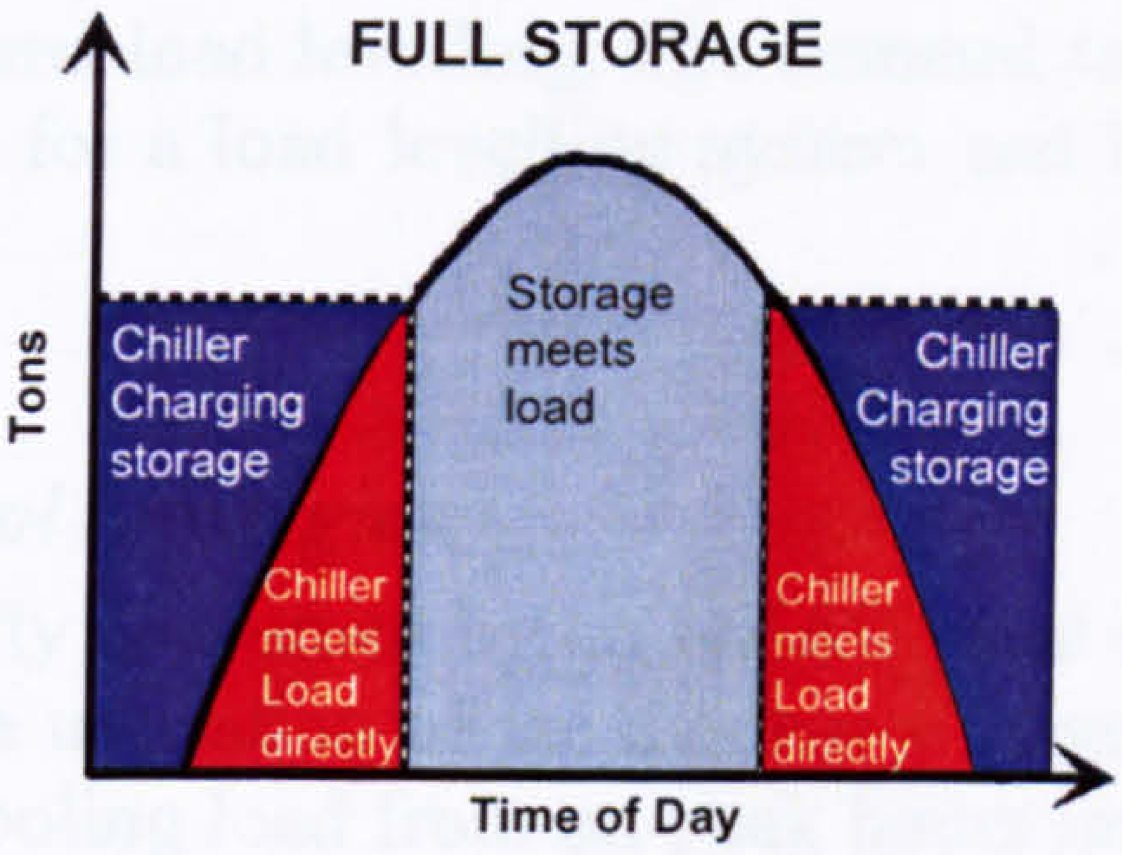

Figure 4.10 Full storage as an operating strategy for ice thermal storage

4.2.2.2 Partial Storage

The partial storage supply strategy shifts a proportion of the cooling demand from the peak demand period by utilising ice storage. Partial storage systems are usually the most practical and cost-effective strategy in new constructions or in on-site space extensions, mainly due to the low capital cost, and is especially attractive when electricity rates provide moderate incentives for load shifting. In partial storage, the storage requirement is smaller than the other strategies because of the continuous operation of the chiller. Two strategies exist within this category and are known as "load levelling" and "demand limiting". Figure 4.11 A and B illustrates the load levelling and the demand limiting strategies respectively.

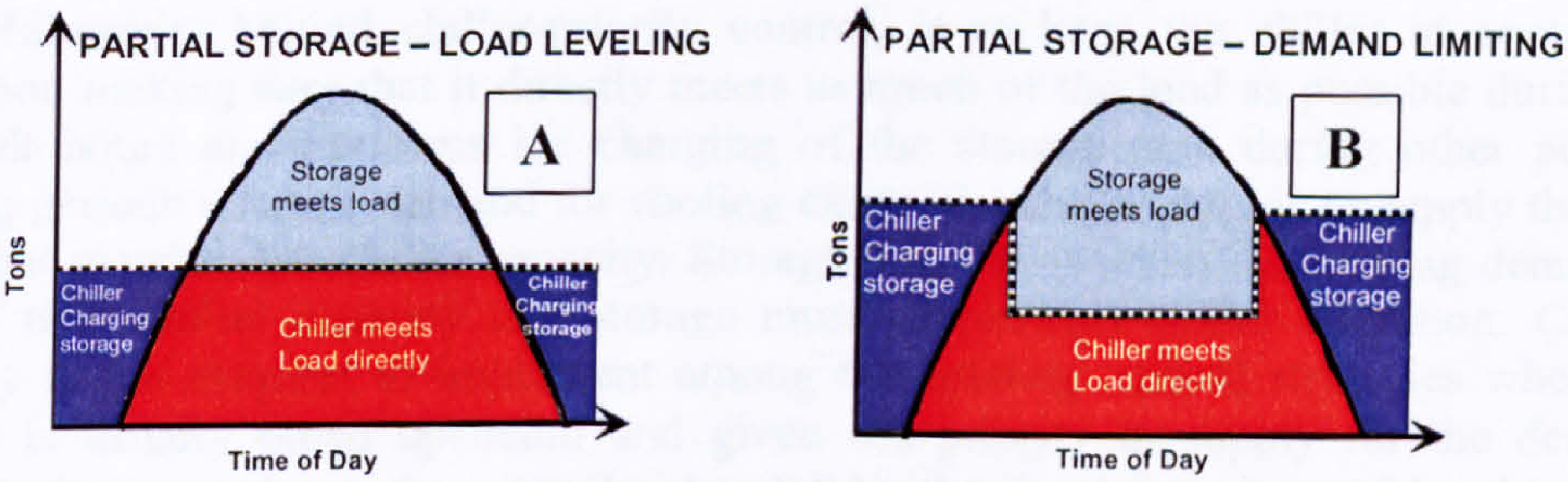

Figure 4.11 Partial storage as an operating strategy for ice thermal storage

Load levelling systems are designed so that the chiller operates at full capacity 24 hours a day. When the cooling load is less than the chiller output, the excess cooling is used to charge the storage tank. When the cooling load exceeds the chiller capacity, the additional requirement is discharged from the ice storage. The chiller is sized at a smaller capacity than the design load and runs at a steady rate over 24 hours. Although the system operates continuously all day, the storage does not meet the peak demand, but supplements the full output of the chiller. This strategy saves about 40 – 60 % of the peak cooling electric demand.

A demand limiting strategy represents a variation of partial storage where the refrigeration equipment operates at a reduced capacity or demand level during the on-peak period. This strategy is most applicable to buildings with significant demand charges and short occupancy periods that allow a greater storage charging time. The demand limiting approach represents a middle ground between complete load shifting of the full storage strategy and load levelling. The demand savings as well as equipment costs are higher than those for a load levelling system and lower than those for a load shifting system.

4.2.3 Ice Storage Control Strategies

Cutting the cost of electricity consumed by an HVAC plant in an office building is the main philosophy behind the utilisation of ice thermal storage. This is achieved through shifting part or the entire cooling load from on-peak hours into off-peak hours. In many countries that utilise different tariffs schemes, optimised control strategies are implemented to minimise the cost of purchased energy. On the other hand, it is important to highlight that any implemented strategy that assure the continuous full load operation of a chiller is more efficient than running it on part load operation. The purpose of thermal energy storage by definition is to increase the load factor of the power grid, i.e. the ratio of average to maximum power demand, so that the installed electricity generation plants are used more efficiently and the construction of future plants can be postponed, Henze (1995).

Chiller-priority, storage-priority and constant-proportion are all optimisation control strategies that fall under the partial storage operation strategy.

4.2.3.1 Chiller-Priority

The philosophy behind chiller-priority control, is to keep the chiller in continuous operation making sure that it directly meets as much of the load as possible during the on-peak hours and performs ice charging of the storage tank during other periods. During periods where a demand for cooling exists, the chiller duty is to supply the base load that matches the chiller capacity. Storage duty starts when the cooling demand is higher than chiller capacity and storage must supplement chiller operation. Chiller-priority is the simplest to implement among the existing control strategies where the chiller is usually piped upstream and given the priority to supply for the demand. Nevertheless, supplementing only the shortfall by the ice storage is considered in some cases as a disadvantage, but this can not be generalised.

4.2.3.2 Storage-Priority

The philosophy behind storage-priority control is to give priority to the ice storage to provide the cooling through the release of the stored energy. This is by melting the ice in the storage tank during the day time. Storage-priority meets as much of the load as possible from stored cooling, using the chiller only when daily load exceeds total stored cooling capacity. Such control strategy is recommended in situation where the cost of stored cooling energy is lower than the cost of instantaneous cooling. In addition, the possibility of achieving a maximum load reduction through utilising this strategy is valid. This is due to allowing the full depletion of the storage tank. Yet, the risk still exist of having the stored ice depleted at an earlier time than it is suppose to be covering for the demand.

While the objective is to maximise the use of stored cooling, it is important to have enough stored cooling capacity remaining to supplement the chiller in meeting high late-afternoon loads. In general, storage-priority operation requires calculating the minimum chiller contribution that will ensure sufficient storage capacity later in the day. Typically performed hourly, this calculation uses a measurement of the amount of cooling remaining in storage and some information about the daily cooling load profile. Storage-priority operation generally requires more complex control sequences than chiller-priority, Dorgan (1994).

4.2.3.3 Constant-Proportion Control

The philosophy behind constant-proportion control is that the cooling demand is supplied by both the chiller and the ice storage through splitting the load equally between both of them. In other words, each cover's up for 50% of the total cooling demand that exist on a day. This strategy is accounted as a compromise between both the chiller-priority and the storage-priority. So, it would offer a greater demand reduction than chiller-priority, but would not satisfy the advantage of using the storage tank to its full extent.

The optimisation of an ice storage integrated HVAC system would clearly rely on a successful intelligent prediction method that would be the base of an implemented intelligent control scheme of the system. Alteration between chiller-priority and storage-priority in most cases is with regards to reducing the cost of energy purchased from the utility supplying the service. At times where the cost of energy is low, the tendency is to operate on chiller-priority control. On the other hand, at times where the cost of energy is high and the cost of cooling supplied by the stored cooling is less, the priority is to go for a storage priority. This argument is valid in the case of countries that apply the time of use tariffs and other similar charging schemes. However, in countries that do not utilise such schemes, such as Kuwait, where the government is the supplier of the service with the biggest part of the cost lying with the government, then a chiller priority would be the recommended control strategy as this would assure the full load operation of the chiller assuring it is running closer to its optimum efficiency. This also would assure narrowing the gap between the average power demand over the maximum power demand, making sure to satisfy the condition of increasing the power factor for the electricity supply system.

4.3 Ice Thermal Storage Researched

The economical aspects of TES generally and ice thermal storage in particular have made many designers pay serious attention to this line of HVAC technology. Although, the literature base that HVAC research has available is considered to be very wide, nevertheless, ice thermal storage represents just a very small percentage of that field. The majority of the research work conducted regarding this topic attempt to benefit and make good use of the different charging tariff schemes that private and/or national power distribution companies or organisations make available for their costumers. As an identified DSM strategy, rebates are often offered to customers to provide incentives to adopt ice thermal storage systems. Tariff schemes that offer financial incentives are some times know as, Time of Use tariffs (TOU). Charging rates are usually associated with time of the day. On-peak periods are usually known as the high cost periods that are characterised with high demand concurrent with limited electricity generating capacity, and a consequent high cost of the unit of energy purchased. On the contrary, off-peak periods are those identified with low demand and an excess of electricity capacity available leading to lower charges on the unit of energy.

While trying to demonstrate how TES is well-positioned to help the move towards more energy-efficient and environmental friendly air-conditioning systems; MacCracken (2003) attempts to set the record straight on the myths and reality of this technology. Several TES research projects, (Beggs-1995, Henze-1995, Francis-1999), report details of the cost-savings aspects of this strategy. However, less emphasis has been given to the potential reductions of equipment size and infrastructure that normally occur. The question often posed is, why install a chiller system that safely meets a load that occurs for only 2 hours a day per year? A simple partial storage system reduces the chiller size to something safely above the average peak daily load, which normally reduces the chiller plant size by about 40% to 50%. MacCracken concludes by stressing off-peak cooling, and stating that off-peak cooling uses low-cost electricity that is efficient to generate and cleaner to make, clearly qualifying it as a green technology.

Silvetti (2002) presents a component sizing approach in simplified terms. For an ice system, chiller capacity is described in two modes – a conventional cooling capacity and an ice-making capacity, which is typically 65% to 70% of the conventional cooling value. A conventional cooling capacity would include the conventional cooling performance required from the chiller to provide cooling to the building. In addition, this might include conventional cooling in addition to cooling discharge from the ice storage at periods where the chiller is unable to meet the demand. For each of the approaches, there is a minimum chiller capacity that can supply all of the required cooling. Applying Silvetti's approach on the ice storage operation strategies mentioned earlier in this chapter would help present a clear illustration of the basic concept.

Full storage is the simplest approach for the selection of a chiller with a minimum capacity and an ice storage that will be able to supply the full demand during the cooling period to the building. Given the approach presented above, assume an office building with a peak load of 50 Tons (176 kW) with a total cooling requirement of 475 Ton-hour (1670 kWh) in 12 hours cooling period.

$$C_{R,tot} = C_{DC} + C_{IMC} \qquad \text{Equation 4.1}$$

where

$C_{R,tot}$ is the total cooling requirement usually given in ton-hours
C_{DC} is the chiller day capacity usually given in ton-hours
C_{IMC} is the chiller ice making capacity usually given in ton-hours

$$C_{DC} = C_{\min} \times h \qquad \text{Equation 4.2}$$

where

C_{min} is the chiller tons, minimum chiller capacity that can supply all of the required cooling usually given in ton *h* is the day hours that represents the cooling period usually given in hours

$$C_{IMC} = C_{\min} \times D \times h_{IM}$$ **Equation 4.3**

where

D is the chiller de-rating when working in ice making mode, given in (%)
h_{IM} is the ice-making hours given in hours

$$C_{\min} = \frac{C_{R.tot}}{[h + (D + h_{IM})]}$$ **Equation 4.4**

$$C_s = C_{R,tot} - (C_{\min} \times h)$$ **Equation 4.5**

where

C_s is the required storage capacity given in ton-hours

$$C_{\min} = \frac{475 ton - hours}{\left[0 hours + \left(0.65 derating \times 12 ice\ making\ hours\right)\right]} = 60 tons$$

Total cooling requirements in equation 4.1 can be obtained from building simulation software. Chiller day capacity represents the conventional cooling process during the cooling demand period, usually during day time. Chiller ice making capacity is the mode that corresponds to the situation when the chiller is in storage charging mode. The storage duty is the supply of demand which is beyond the capacity of the chiller to provide. In this case the storage requirement is the entire 475 ton-hours (1670 kWh) of the design day cooling load. It can be seen that the required chiller capacity is actually larger than the 50 ton (176 kW) that would have been needed in a non-storage application. Furthermore, it is commonly known that the chiller size in a full storage application is approximately equal to the non-storage alternative. This strategy is usually the most expensive option compared to other operation strategies of ice storage systems. Nonetheless, it is most common where extended payback periods are acceptable or where incentives or rebates are offered, such as an off-peak tariff.

A partial storage strategy is often designated by designers as it reduces or minimises the installed chiller capacity. For such an option, a fully loaded chiller operates continuously throughout a cooling design day. Application of the formulae, equations 4.1 – 4.5 as above, is identical to the case of a full storage strategy. Yet, the day hours that represents the cooling period must be accounted for. Assuming a 12 hour period operating in ice-making hours mode and 12 operating day hours operating in conventional cooling mode.

$$C_{\min} = \frac{475 ton - hours}{\left[12 hours + \left(0.65 derating \times 12 ice\ making\ hours\right)\right]} = 24 tons$$

$$C_s = (475_{ton-hours}) - (24_{tons}\ x\ 12_{hrs}) = 187_{ton-hours}$$

Table 4.1 Comparison of a different system design conditions

System Type	Chiller Tons	Storage Ton-Hours	On-Peak Chiller	Percent of Total Load
Conventional	50	0	50	100
Full Storage	60	475	0	120
Partial Storage	24	187	24	50

Chiller tonnage is reduced to approximately 24 tons (84 kW) and the storage requirement drops to 187 ton-hours (kWh). The effect of each strategy on a single office building becomes clear, see table 4.1. Depending on the existence of on-peak and off-peak charging schemes, the advantage of prioritising one over the other can be decided up on. Indeed, in the case of a country like Kuwait, where electricity charges are highly subsidised in addition to the existence of a single tariff scheme, the utilisation of a partial load strategy would be more promising on national level and for the consumer.

From table 4.1, it can be observed that a full storage option eliminates any chiller contribution to the on-peak demand and shifts most of all of the chiller energy to off-peak periods. Partial storage avoids half of the on-peak chiller demand but both chiller and storage capacities are well below half that required for full storage, minimising initial investment costs.

Generally, the energy efficiency of a cooling system is characterised by its Coefficient of Performance (COP). The COP is defined as the ratio of the rate of heat extraction (Q_{ext}), in kW, divided by the rate of energy input required (W_{in}), in kW, Krarti (2000). Levermore (2000), for a perfect cycle calculates the COP to be equal to 7.83. However, Levermore states that this is for a perfect cycle and in reality the practical COP is approximately half this, COP $\approx$ 4. In the case of an electrically driven cooling system, the COP can be expressed as:

$$COP = \frac{Q_{ext}}{W_{in}}$$ **Equation 4.6**

Dorgan (1994), provided a comparison of primary features of cool storage systems. In his comparison, it is stated that the COP of a cooling plant with ice storage ranges between 2.5 to 4.1. The variation depends on several factors. For example, an examination of manufacturer's chiller data shows that cooling capacities vary with the variation in the ambient temperature (T_b), in ^oC. Likewise, cooling capacities are affected by the variation of the chiller outlet temperature (T_{cho}), in ^oC. Table 4.2 demonstrates the different cooling capacities of a chiller that can be used in association with ice storage within the cooling plant. Values for the COP for the highlighted system in Table 4.2 are represented in Table 4.3

Table 4.2 Variation of chiller energy input rate and cooling capacities with the chiller outlet temperature T_{cho} and ambient temperature T_b: 30% Ethylene glycol, (YORK)

T_b \ T_{cho}		-8	-6	-4	-2	0	2	4
30	Q_{ext}	195	212	230	247	265	245	305
	W_{in}	72	75	78	81	84	87	90
35	Q_{ext}	183	200	217	234	252	270	290
	W_{in}	74	77	81	84	87	90	95
40	Q_{ext}			205	220	239	256	275
	W_{in}			83	87	90	94	98
45	Q_{ext}				207	224	241	260
	W_{in}				90	94	98	102
50	Q_{ext}					209	226	245
	W_{in}					97	101	106

Table 4.3 Variation of chiller COP with the chiller outlet temperature T_{cho} and ambient temperature T_b, (YORK)

T_b \ T_{cho}	-8	-6	-4	-2	0	2	4
30	2.71	2.83	2.94	3.05	3.15	2.81	3.39
35	2.47	2.60	2.68	2.78	2.89	3.00	3.05
40			2.47	2.53	2.65	2.72	2.81
45				2.30	2.38	2.46	2.55
50					2.15	2.24	2.31

The data shown in tables 4.2 and 4.3 indicate that as the chiller output temperature decreases and the ambient temperature increases both the output capacity and the COP of the chiller decreases, while the required energy input increases. This effectively means that the system runs less efficiently during the ice making mode and during the hottest parts of the year.

In a project consisting of installing an ice storage chilled water cooling plant, Haughey (2003), states that the chiller system uses about 40% less electrical demand than a chilled water system without thermal storage because of the smaller chiller. It represents a demand limiting partial storage system that allows the system to use ice to reduce demand during peak times by modulating back the chiller while automatically increasing cooling provided from ice storage. Further cost and environmental benefits were realised because the lower chilled water temperature allowed reduced distribution piping sizing.

Haughey affirmed that with accounting for improved demand savings from utility bills, the data show a total savings of $18,284 per year for a payback period of 4.1 years. In comparison with a typical chiller system, operating efficiency is improved by freezing ice during cooler nights and by running the chiller solo during the morning when it is still cool outside.

A mechanistic model was developed to simulate the time dependant performance of the static ice-on-coil storage tank, Jekel (1991). The model was based on analysing the water melting and freezing around the coils. An energy balance was applied on the contents of the tank to derive the governing equations for heat transfer rate related to the tank. Subsequently, the heat transfer rate from the brine to the ice; the heat transfer rate from the ambient to the ice; and the rate of change in the internal energy of the storage medium were derived. The latter was broken down into the sum of latent and sensible changes in the ice and the sensible change in the water. The tank model was base on the log mean temperature difference (LMTD) heat exchanger analysis. Both the charging and discharging periods of the tank operation were modelled and compared with manufacturer's performance data. The model was then run at different flow rates, different brine outlet temperatures, and with varying numbers of finite lengths. The convergence of the outlet temperature with increasing discretisation of the space parameter related was studied. The resulting data was plotted against the performance data of the ice storage manufacturer, Calmac, to determine minimum discrete volume of the coils needed to obtain agreement between model and experiment. Then, a comparison was provided to show the trends in design for conventional and variable flow systems with and without ice-storage. The conclusions were that, systems with ice-storage required smaller chillers than for the corresponding systems without storage and the variable flow systems required less total energy and smaller chillers in relation to the corresponding conventional systems. Also, another achievement was the minimisation of air-conditioning load, which was accomplished by reducing the sensible reheat required by the same system. A fraction of the relatively warm return air flow rate was mixed with the air-conditioner coil outlet in order to reduce the reheat.

Strand (1994), described the development of models for both direct and indirect ice-storage systems and discussed their salient features as applied to energy analysis calculations. The goal was the development of such models for implementation into the BLAST (Building Loads Analysis and System Thermodynamics) energy analysis program, BSL. The author described the derivation, development, and implementation of an ice storage system model in BLAST. For an indirect ice-storage system, generalised heat exchanger equations that could be used to define the performance of any indirect ice-storage system were used, along with manufacturers' data and a least square fitting program, to construct the indirect ice-storage system models. The models could be adjusted to other available ice-storage systems. This was the initial step in a process of the development of accurate storage models for use in HVAC engineering modelling research.

Henze (1995) identified control strategies for ice storage systems that reduced operating costs in commercial buildings. He developed an optimal control strategy that minimised the total electricity cost combining energy and demand charges. The objective was achieved through computer simulation of a variety of representative commercial building energy systems. For each representative building energy system, an optimal storage control strategy was developed to minimise system operating cost.

The optimal control strategy was compared to conventional controls including chiller priority, constant-proportion, and storage priority control. The finding was that, optimal control was shown to succeed in saving money. Among the conventional control strategies, storage-priority performs the best. Under real world conditions, the future loads even a few hours into the future cannot be perfectly predicted. Henze also concludes; not only the charging and discharging strategy have to be optimised in real time, but operation of the cooling plant in general was of concern. Part of the merit of selecting a good strategy may be lost if the cooling plant itself operates inefficiently.

Consequently, developing an intelligent control strategy only might be a good choice. However for a satisfactory optimised HVAC plant with integrated ice storage plant, the a model based predictive controller would help to achieve better results for optimum operation of the cooling plant as a whole and not only as part of the plant. Hence, this research work aimed to utilise model predictive control to optimise the cooling process as a whole through the integration of an ice storage model associated with the plant.

The work presented by Francis (1999) was undertaken with the intention of exploring the role of 'Soft Computing' techniques in supervisory control. Representation of the dynamic behaviour of a single zone building with a central refrigeration plant and an internal-melt-ice storage system was undertaken. The chiller upstream ice storage system aims to present the state changes that occur within a system rather than an excessive level of detailed dynamics. Utilising a genetic algorithm for scheduling and fuzzy logic and neural networks for system identification was the methodology used for this demand management approach. This work demonstrated the possibility to adopt a flexible approach to load management using ice storage. The work was also aimed at optimising the running cost to achieve the lower cost associated with ice priority.

Beggs (1995) introduced a time block model that could be used with an ice storage model to design and optimise ice storage installation in the context of electricity contract market in the UK. The time block model was to be used with pool priced electricity contracts. However, the time block model appeared to have a weakness in which it could not fragment in order to gain maximum potential from avoiding short peaks, or by utilising short troughs in the electricity price.

4.4 Conclusions

Through the research literature review introduced in the preceding section, it can be seen that most of the research work and investigation conducted to date aims to optimise the use of ice thermal storage systems through the identification and selection of the optimal price that can be reflected in reduction or savings in the running cost. This is very useful for nations that have a power industry, where real time pricing is functional and the power generation, distribution and selling are dealt with on a basis where profit is the first priority. In such a situation, an operation strategy can be introduced that would consider cost effectiveness to be more important than energy efficiency as the target is to make good use of the low price of electricity at some particular time.

On the other hand, for nations that do not implement real time pricing and the power production is part of the public sector such as Kuwait, and where the cost of unit of energy (kWh) is much higher than the price charged to the costumer, the priority is for utilising operation strategies that would help achieve reduction in the peak demand that is caused by instantaneous cooling that leads to the requirement for the instantaneous electricity generation sufficient to meet that load. The main benefit utilising such strategies would be to make efficient use of the available power generation capacity on national level. In addition this would limit the need for new power plant by extending the number of years required for new construction to a longer period.

"Reducing the energy consumption of buildings requires that the energy problems be known. There cannot be an elegant solution to a misstated problem" ... [Rittelmann, Energy Conservation & Management Strategies], from Hunn (1995)

Chapter 5

Examination of Demand Side Management through Zoning & Plant Modularisation – The Building & HVAC Models

5.1 Introduction

The use of building simulation software enables users to calculated dynamic cooling and heating loads for zones in buildings or even a building as a whole. A description of thermal properties and dimensions of building components such as walls, floors, ceilings, and windows is required. In addition, weather data for the building location must be employed. Furthermore, a schedule of energy gains from equipment, lights, and people must be known. Building simulation software are used to size heating, ventilation, and air conditioning (HVAC) equipment by estimating peak cooling or heating loads for buildings. Over-sizing HVAC equipment results in excessive capital cost for equipment and extra energy costs due to inefficient part-load operation of equipment. Under-sizing HVAC equipment results in unacceptable comfort conditions for building occupants.

This research work aims at the adoption of Model Predictive Control (MPC) strategies for the optimisation of the use of integrated ice storage systems utilised within office buildings. As part of the work, investigation on the effect of specific zones on a building cooling load is investigated.

In order to be able to examine the aims and objectives of this research work, a single zone dynamic building model was simulated. and representation of an office building in the form of a single cell was simulated using both the Thermal Analysis Software

(TAS),and Matlab modelling tools. TAS was used as a base for studying and analyzing the different type of occupancy patterns carried on in Kuwaiti office buildings. TAS was also used to examine the effect of orientation on the cooling load. With the tools it is equipped with, Matlab was chosen to be the ground base for building the building representation with the Heating, Ventilation and Air-Conditioning (HVAC) system. A comparison of performance between the TAS model and the Matlab model was conducted which validated the use of Matlab as an academic tool for the modelling and implementing of the control strategies under investigation.

5.2 Buildings and their Stereotypes

Part of the objective of this work is to examine the load profiles of typical office buildings in relation to orientation to ascertain how control zoning and energy storage might be used to flatten electrical load demand. To examine how a real building will behave dynamically, a model or prototype of it is required to be simulated.

The design process requires the examination of design objectives to achieve a satisfactory basis for a solution. Architects often begin this process by considering stereotypes for given building types. Several stereotypes exist for office buildings. In order to assess how building form might affect the achievement of the objective, simulated models of office buildings should represent stereotypical forms of modern office buildings.

The modelling process usually starts with an examination of existing stereotypes and these should be subjected to a process analysis in which the output can be evaluated and compared against the stated objectives. In order to satisfy this, an examination of typical modern office building forms is required to develop standard plans for thermal modelling.

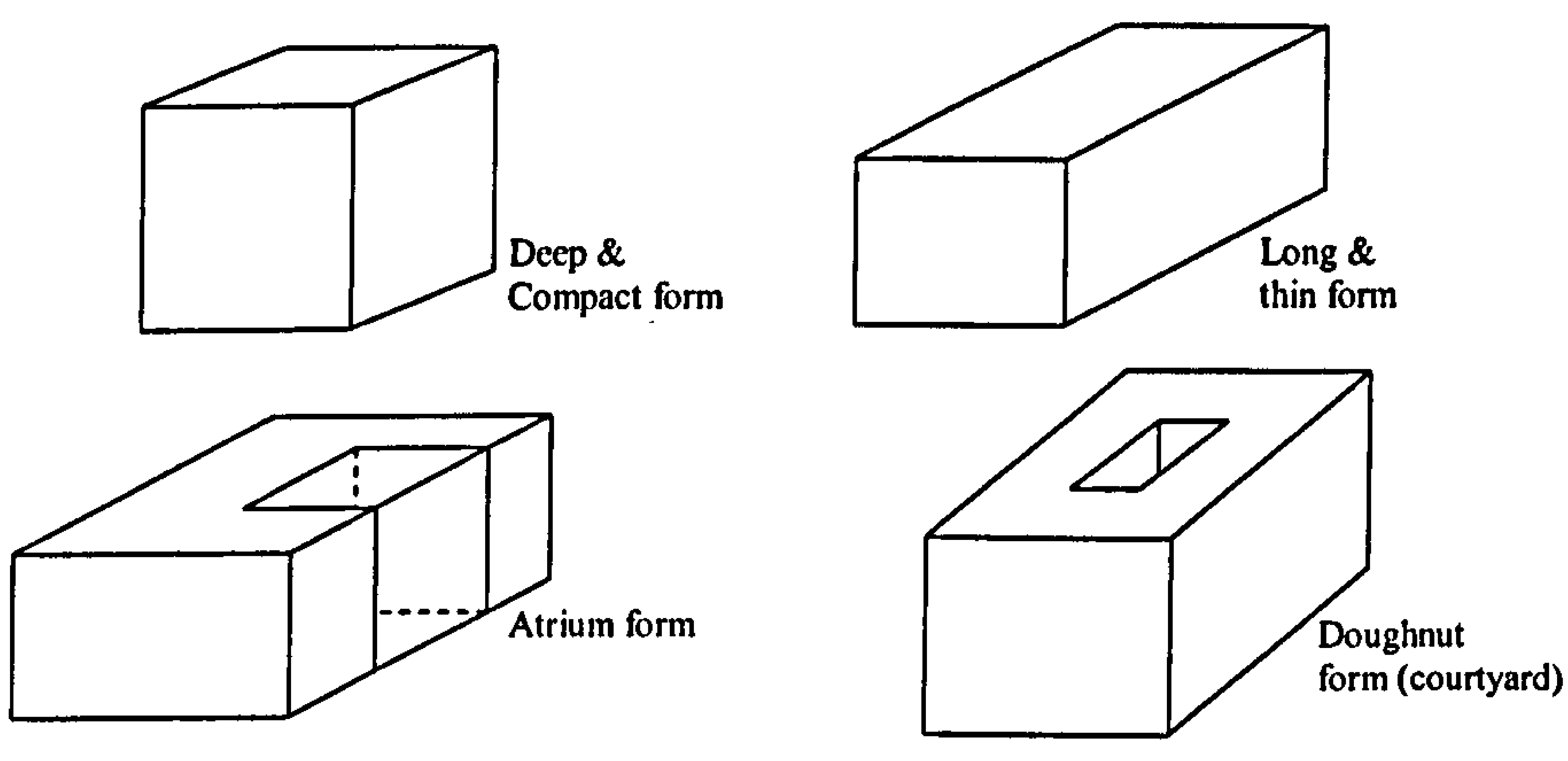

Figure 5.1 Different layout of the stereotype and forms of office buildings

The form and function of office buildings has evolved considerably during the 20th century. Building services present in the form of complex mechanical systems are now a major part of modern office buildings. A number of different kinds of stereotypes exist at present. Yamakawa (1997) addressed four types or forms of stereotypes that exist currently and these are reproduced in figure 5.1. These have been drawn from the work of Hawkes (1976) and represent common forms that may act as starting points for current design. The key features and attributes of each stereotype are listed. Each stereotype has been considered in the context of the current office building stock in Kuwait.

5.2.1 Deep and Compact, low aspect ratio

- The internal spaces adjacent to the external walls can be daylit, but the central area, which has no external walls, requires the use of artificial lighting.
- It may be intended to control the indoor environment within narrow limits: interior spaces require careful servicing and may need comfort cooling as well as mechanical ventilation. Required illumination levels are achieved by the use of artificial lighting in interior spaces
- This form presents a low surface area to contained volume ratio and is often considered to provide lower energy consumption rates than other stereotypes.

5.2.2 Long and thin form

- This form can have a shallow plan.
- It allows the use of daylight and natural cross-ventilation.
- The office floor is fully daylit up to a depth of 6 meters. The room depth could be up to 12 meters if it has windows on the 2 opposite walls.
- The window areas on south, east and west facing walls may require solar shading devices.
- Artificial lighting can be used to supplement the daylight during the daytime and at night.
- This form could have an atrium on one long side.

5.2.3 Atrium form

- Atria can act as light wells that allow daylight to penetrate into the bulk of a building.
- 15 meters floor depth or narrow plan (12 meter wide floor plates) can be fully daylit.
- Solar control devices such as blinds and sunscreen may need to be fitted to maintain thermal and visual comfort.
- Artificial lighting with control may be essential.

5.2.4 Doughnut form

- Courtyards can provide the access to daylight and view to more parts of the building.

- For taller the buildings the courtyard becomes less effective in providing daylight at lower levels.
- Courtyard can also provide access for cross ventilation.
- The courtyard can also be covered with glass to provide an atrium space.

5.3 The development of stereotypes for modelling

Since late 1970s and early 1980s, office buildings in Kuwait have been designed based on the modern international styles or stereotypes of office buildings. High-rise office buildings of between three and fourteen storeys have become common. Such buildings are constructed using concrete and heavy masonry materials. A range of glazing types is used in such buildings. Earlier buildings used moderately large areas of single glazed windows and this continued until the late 1980s. However, the current trend is to use multiple glazing such as double-glazed windows with some form of solar control glass within the glazing system. The figures below clearly show the general form and style of current office buildings in Kuwait.

Figure 5.2 The three banks space in Kuwait

Figure 5.3 Kuwait Ministry of Information, TV and Radio Broadcast Building

Figure 5.4 (Top) & (bottom) show aerial views of two different locations in Kuwait

As can be seen from figure 5.2 to figure 5.4 that the most common forms of modern office buildings found in Kuwait represent either the "deep plan" or "long thin" stereotypes. Consequently, to satisfy the objective of this work, these two forms of building plan have been chosen. These, in effect allow the implications of two extremes of design stereotype to be examined and compared.

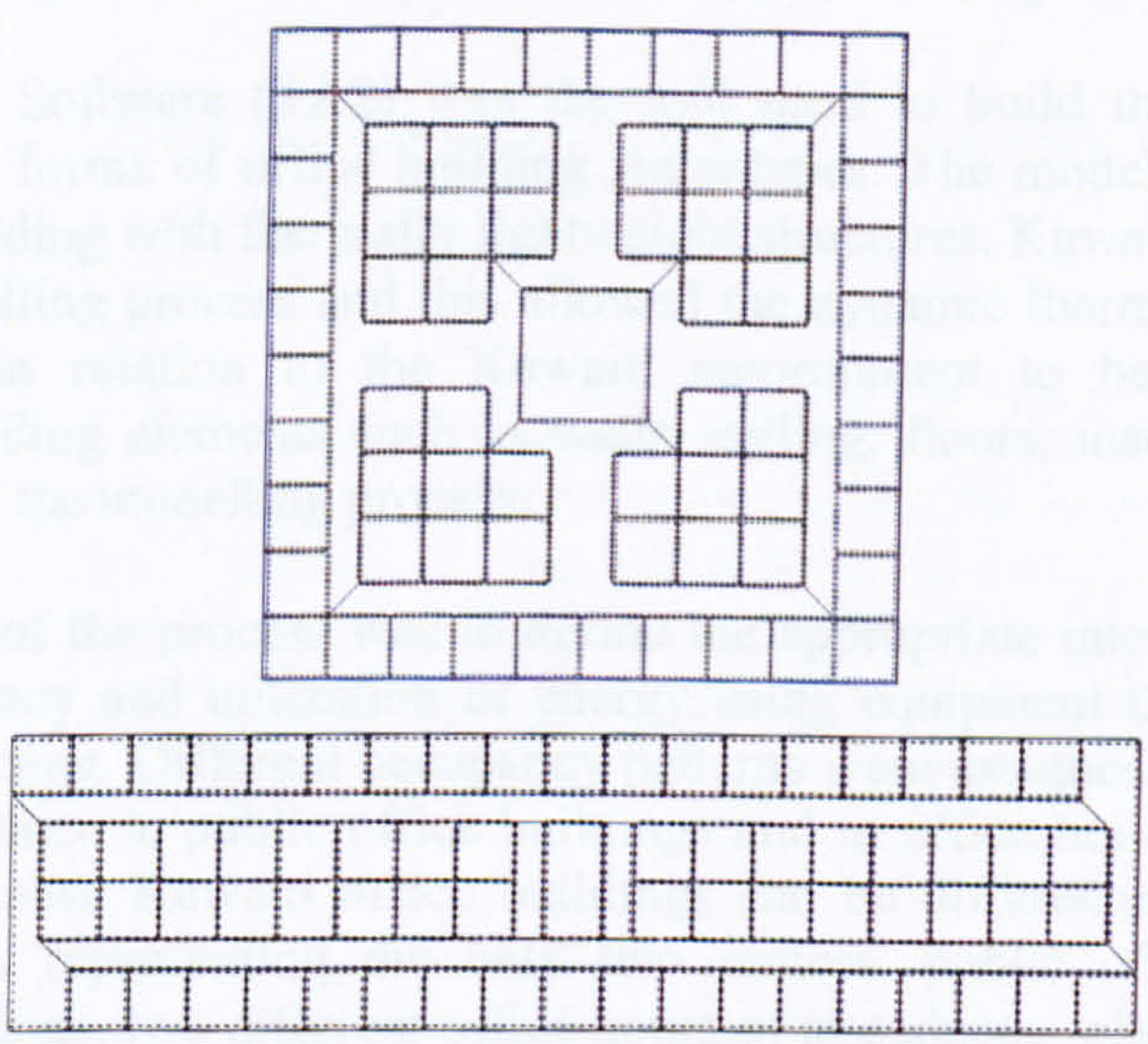

Figure 5.5 Two forms of layouts chosen for consideration: (top) deep plan and (bottom) long thin

Examination of the effect of external conditions on offices placed in different orientations will be conducted. The selected two types of layout will be used to ascertain the load profiles in relation to orientation and consider how these might affect the development of building environmental services control zoning and the development of strategies for energy storage. Utilising the design stereotypes considered earlier two representative floor plans were developed as shown in figure 5.5.

5.4 Electricity demand management for office buildings in Kuwait

The main goal of this research work is to examine the use of energy for environmental services in office buildings with a view to reduce the overall and the peak consumption rates. This can be achieved first through the careful design of buildings and their systems but can be further enhanced through the examination of potential strategies to control air conditioning systems efficiently.

To achieve this it is important to understand the nature and characteristics of modern office buildings and the relationship between the current stereotypes and the local climate.

5.4.1 Models Developed

The development of the two model buildings that represents the two most common forms of stereotypes in Kuwait provided a base from which to reflect the dynamic thermal behaviour of a specific building type. The main aim is to investigate and examine the different patterns of the electrical load with reference to the thermal behaviours of specific zones at different orientations and how this might affect the development of a building's environmental services control zoning. With this the development of strategies utilising energy storage could be investigated in relation to controlling the electrical demand patterns within office buildings in Kuwait.

Thermal Analysis Software (TAS) was the tool used to build the dynamic thermal models of the two forms of office building stereotypes. The models represent modern types of office building with thermally lightweight structures. Kuwaiti weather data was set up in the modelling process and this allowed the dynamic thermal behaviour of the building models in relation to the Kuwaiti environment to be investigated. The assignment of building elements such as walls, ceiling, floors, insulation and double-glazing was part of the modelling process.

An important part of the process was to define the appropriate internal conditions, i.e. patterns of occupancy and utilization of energy using equipment that are related to a Kuwaiti office building. Different occupancy patterns were assigned that represent both office hours attendance in public office buildings and in office buildings related to the private sector. Because Kuwaiti office buildings can be differentiated into two main occupancy patterns representing the only two sectors, public office buildings and private office buildings, two different office hours of attendance schemes were used for the simulation of each stereotype. This allowed the development of options for implementing demand side management operation strategies utilizing cool storage in such buildings. In addition, this would allow the evaluation of the effects of each strategy and help to ascertain which of them provided the best option for adoption.

The occupancy scheme used to represent the public buildings sector office daily hours of attendance was for occupation was assumed to occur between 07.00 am and 15.00 pm. For the private sector, the daily office hour's of attendance was taken to be between 9.00 am to 13.00 pm and 16.00 pm to 20.00 pm.

In most office buildings in Kuwait, the common practice during the summer season is to leave the air conditioning system running at a fixed temperature for all 24 hours per day, regardless of the occupancy periods and whether they were occupied or not. Referring to Al-Mumin (2002), occupants tend to leave all lights on even when the rooms are vacant, and they prefer to keep the room cooler with the A/C thermostat set at 22 °C. These behaviours related to similar occupant behaviours in Kuwaiti residences.

5.4.2 The office cell, the different scenarios and internal conditions

Figure 5.6 below presents the layouts of the office buildings modelled. Internal heat gains are accounted for in the model and chosen on the bases described below.

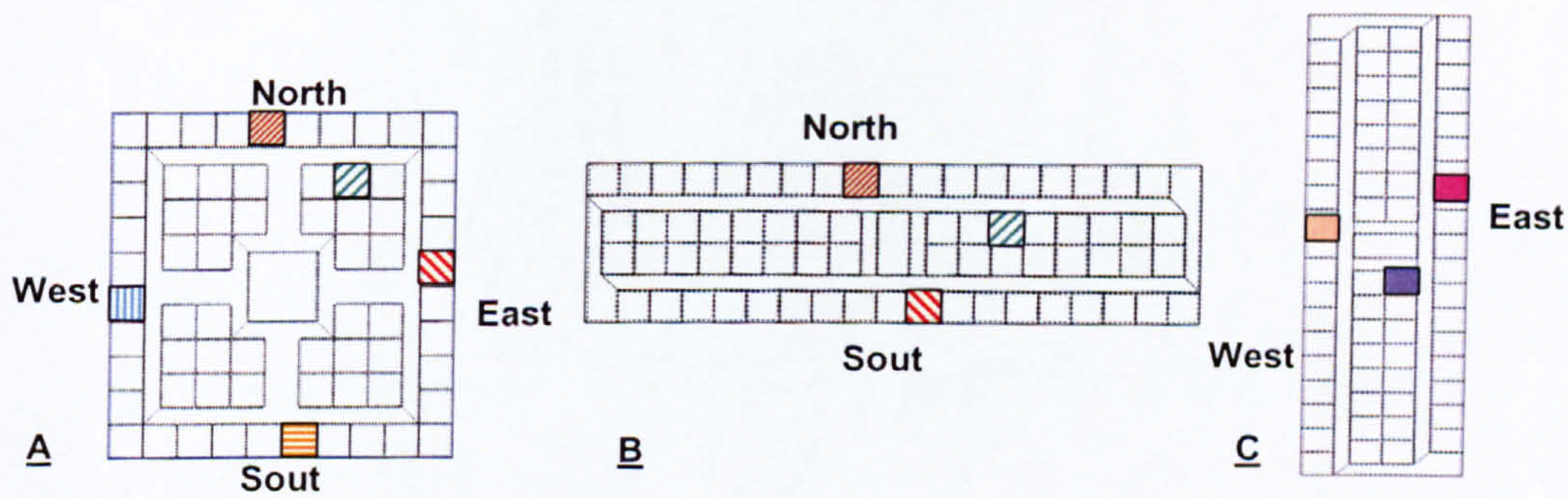

Figure 5.6 Layout of both stereotypes with different orientations and zoning

5.4.2.1 Occupancy

The modelled office space was set up with a length of 6 meters, width of 6 meters and height of 3 meters. Occupants were assumed to be seated with an activity level relating to very light work. Each office cell was assumed to accommodate 6 individuals. Referring to the ASHRAE Handbook, Fundamentals 2001, chapter. 29, table 1, the total heat gain from occupants was set to be 115 W with the sensible and the latent heat gains having the values of 70 W and 45 W respectively for each individual.

5.4.2.2 Lighting

Lighting in the offices was assumed to utilise fluorescent fixtures, 1200 mm long, T12 "Energy Saver" lamps with 2 tubes per luminaire. Each office was provided with 10 fixtures per office with 68 W for each lamp. From the ASHRAE Handbook, Fundamentals 2001, chapter 29, table 2, this translated to an electrical power input of 20 Wm^{-2} for lighting.

5.4.2.3 Equipment

Deciding on the electrical power input for electrical equipment presents difficulties. Assuming this to be identical to the sum of the power ratings shown on equipment nameplates has led to the overestimation of this input. The ASHRAE Handbook, Fundamentals 2001, chapter 29, figure 4 explains this issue in terms of diversity testing showing that the actual heat gains per unit area, or load factor, ranged from 4.7 to 11.6 Wm^{-2}. The relationship between nameplate power rating and actual consumption rate is illustrated in figure 5.7. Utilising this model and referring to the assumed nameplate load factor for office equipment a value of 10 Wm^{-2} was decided for heat gain from equipment.

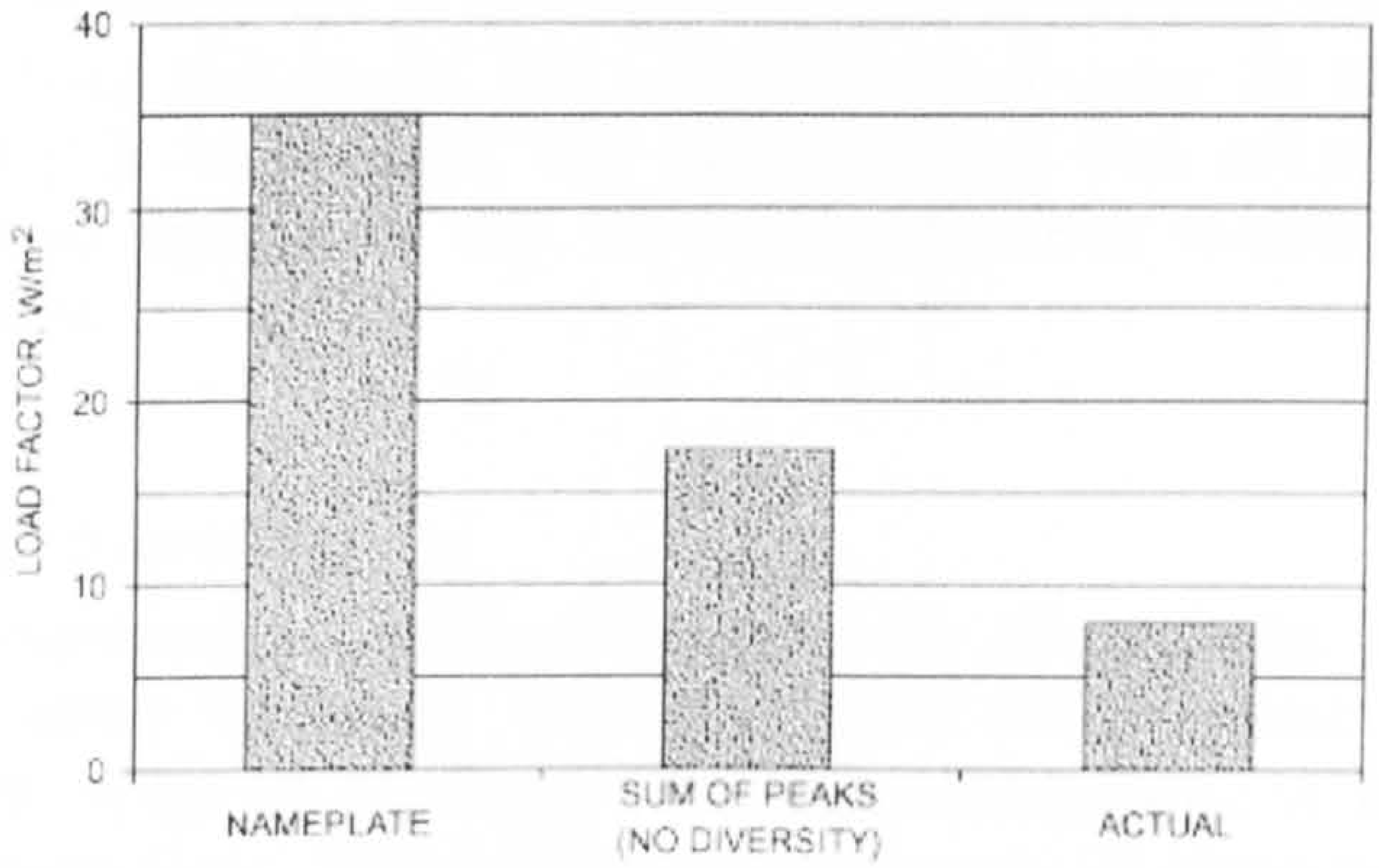

Figure 5.7 Office Equipment Load Factor Comparisons, (ASHRAE 2001)

5.4.2.4 Scenarios of Operation

5.4.2.4.1 Scenarios for the deep plan building – Figure 5.6 (A)

A. In scheme (A) a single office cell on each orientation and one cell representing an internal office were zoned and simulated. The four external office cells were orientated north, east, south and west respectively. Office occupancy hours were set as for the public sector with occupancy between 7.00 am and 15.00 pm and A/C systems, lighting and other electrical equipment were set to work between the hours 6.00 am and 15.00 am. The A/C plant and the equipment were assumed to be switched off during non-occupancy periods and during weekends for the base model.

B. The second model retained the same zoning and hours of occupancy as scheme "A" but the internal conditions were modified so that the A/C, lighting and office equipment were left running for 24 hours including weekends.

C. Scheme (C) retained the same zoning as the previous schemes but the office occupancy hours were changed to be between 9.00 am to 13.00 pm and 16.00 pm to 20.00 pm, as for private sector offices. A/C system, lighting and other electrical equipment were set to work between the hours 7.00 am and 13.00pm, and 15.00 am and 20.00 pm. A/C system, lighting and other electrical equipment were switched off during non-occupancy periods and during weekends.

D. Scheme (D) retained the same zoning but office occupancy hours were set between 9.00 am to 13.00 pm and 16.00 pm to 20.00 pm. The A/C system was set to work between the hours 7.00 am and 20.00pm, while the lighting and electrical equipment were switched off between the hours 20.00 pm and 7.00 am, and during weekends.

5.4.2.4.2 Scenarios for the deep plan building – Figure 5.6 (B & C)

The same schemes were applied to the long thin type of building model, except that for the orientation, the long thin model was manipulated to cover all four orientations, see figure 5.6 (B) and (C). In addition one more scheme was added where A/C plant, lighting and electrical equipment was set as continuously working regardless of the office occupancy hours.

5.4.3 Exploring the results

To ensure that similar assumed conditions applied for all zones the building model was not surrounded by other buildings. This eliminated the potential effects of shading occurring at different times of the day for different orientations. A full year simulation was conducted for each zone. Several days were chosen for close examination so as to represent the range of behaviour relating to the summer season. A clear view emerged of how the daily air-conditioning load varied during specific days during the summer season. The designations in figure 5.8 relate to schemes A and B as previously described.

Figure 5.8 displays the results for a deep plan building representing a public office building. The individual zones showed distinct differences of behaviour in relation to orientation. For example, figure 5.8, A1, A2, B1, and B2, display how orientation affects the daily load variation; with different orientations experiencing peak loads at specific and different times during the day. During the first half of the day the cooling load of the east zone displayed the highest peak. This behaviour is related to the sun path position. The east-facing zone of the building is the first to face the sun during early part of the day. The sun angle is low and so the rate of solar gain through the window of the zone will be high.

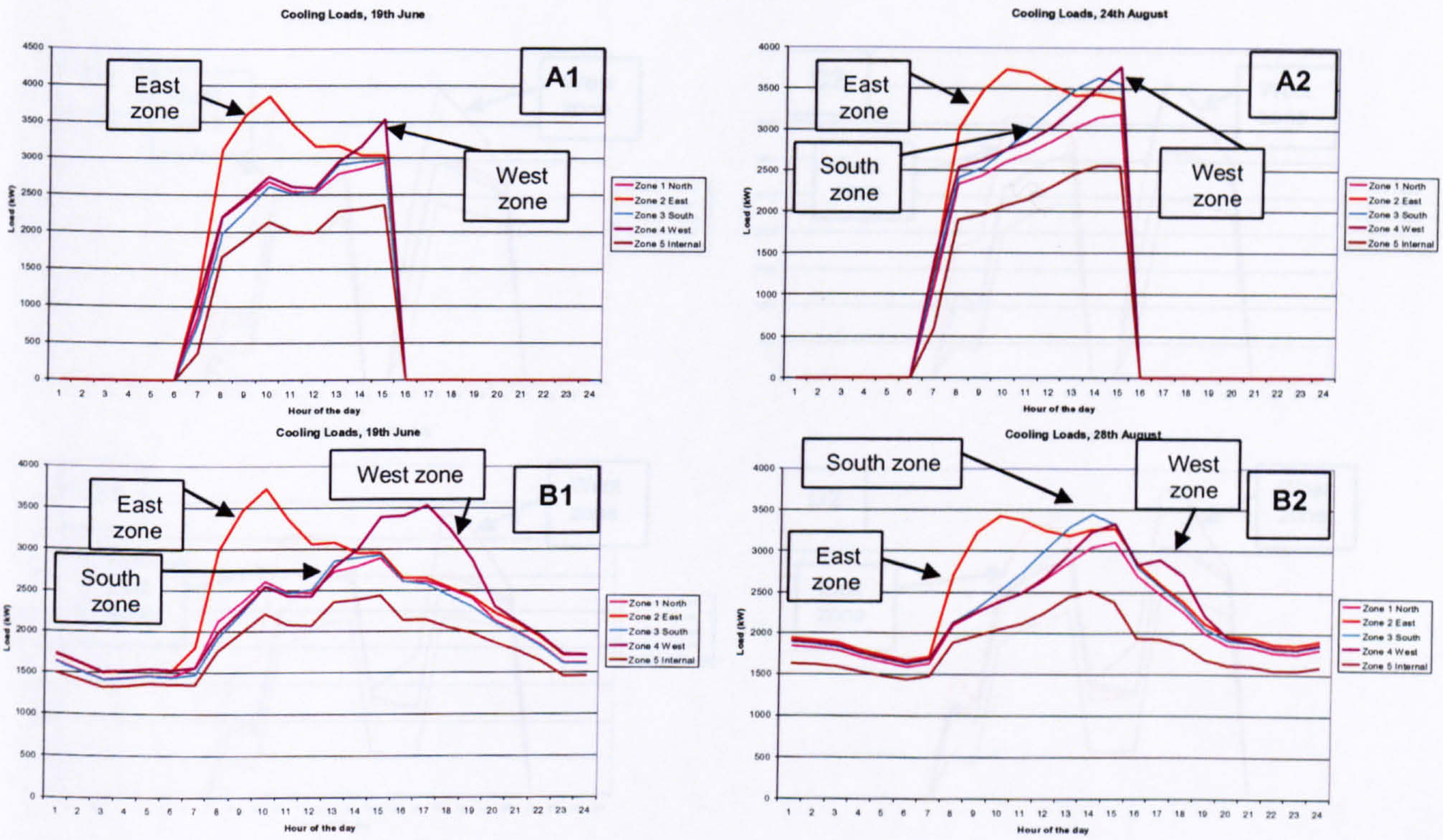

Figure 5.8 Load profiles for the deep plan building representing a public building, where A and B relate to the designated occupancy schemes

By mid-day, the load is increasing in the other zones but especially in the south zone, as the sun is now located to the south of the building. However, although at solar mid-day the solar irradiation is at its highest value the south facing zone does not necessarily experience the highest peak load. This is because the sun angle is now very high and the window glass is highly reflective to the incident radiation. During the afternoon the sun angle is becoming lower and approaching the west. Consequently, the load increases in the west zone of the building and it becomes the main source for the cooling load. This can be seen in figure 5.8,A and B, above.

Figure 5.9 represents the results for the deep plan building model, but representing a private sector office building and the designations C and D relate to the schemes previously describe. These display the same kind of behaviour as for figure 5.8 for schemes A and B. However, because of the nature of the hours of occupancy, the mid-day peak profile for the south zone does not appear to be one of the major contributors to the cooling load for the model.

Figure 5.9, C1, C2, D1 and D2, represent the private office scenarios where the HVAC and electrical equipment are only running between 7.00am to 13.00 pm and 15.00 pm to 20.00 pm. For figure 5.9, D1 and D2, only the A/C is kept running without being turned off during the mid day break between 13.00 pm and 16.00 pm. Again there is a clear differentiation between the times of the day when peak load occurs for different orientations.

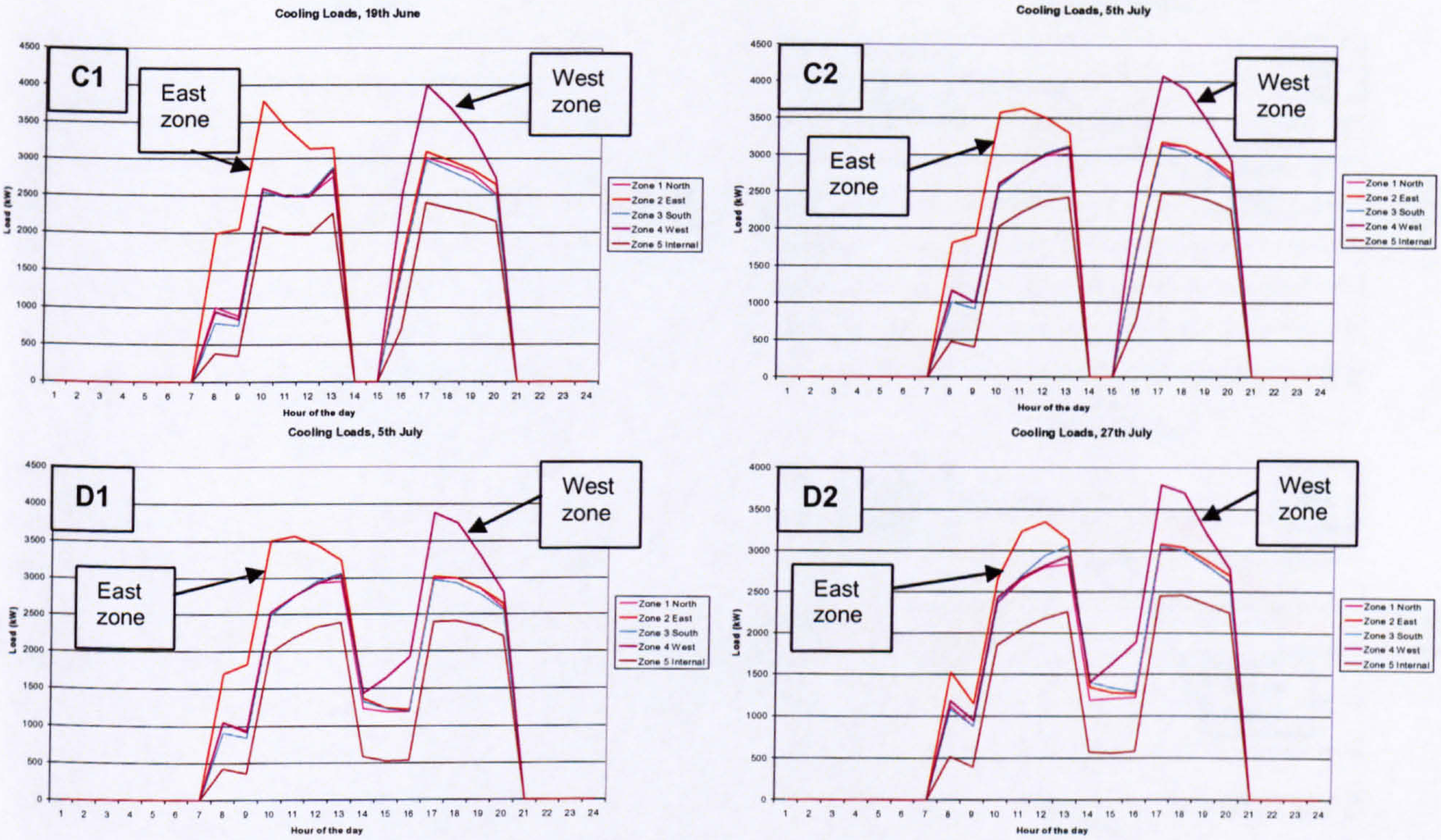

Figure 5.9 Cooling load profiles for a deep plan building representing a private sector office building, where C and D relate to the designated occupancy schemes

For the thin long building model, as displayed in figure 5.6, external office cells are oriented either north and south in one case or east and west in the second case. Figure 5.10 shows the results for the north-south orientation. When applying the public sector scenarios, A and B.

Initially the profiles for the north and the south office cells are similar, however approaching noon and for some period afterwards the loads within the south zone becomes higher than those in the north zone.

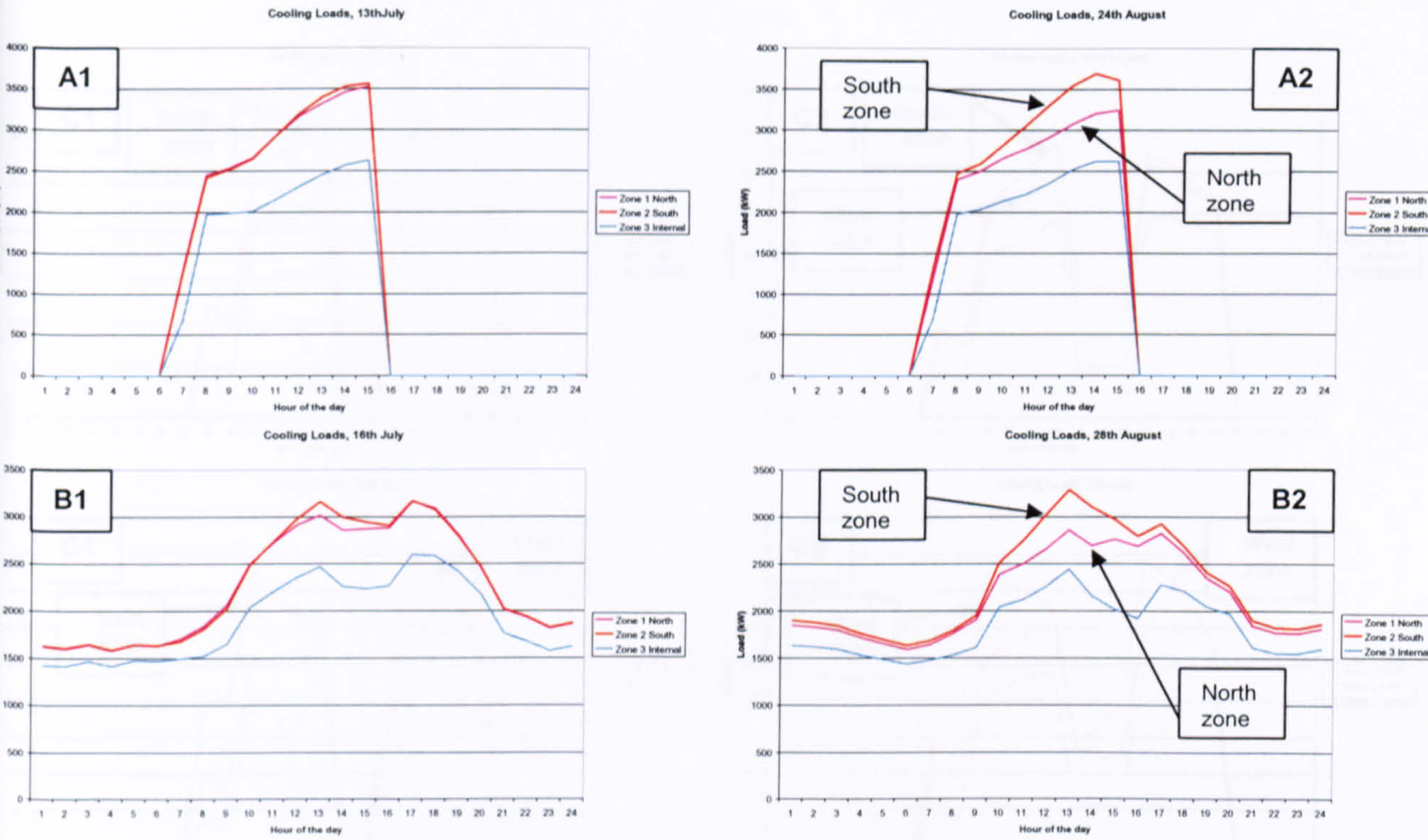

Figure 5.10 Load profiles for the long thin building representing a public building with offices having north and south orientations

Figure 5.11 shows the load profiles for both the east and west zones, when the building orientation has been changed. Again the load profiles for the east and the west zones tend to form two peaks at different times during the day. In the case of the thin long building model, representing a private sector office building, cooling load profiles for both models with north and south offices, and with east and west offices are displayed below. Again, the same happens for the building with the north and south zones, where they tend to act the same to some extent, figure 5.12 A and B. For the building with zones at the east and west orientations, both zones tend to form two high peaks at different time during the day.

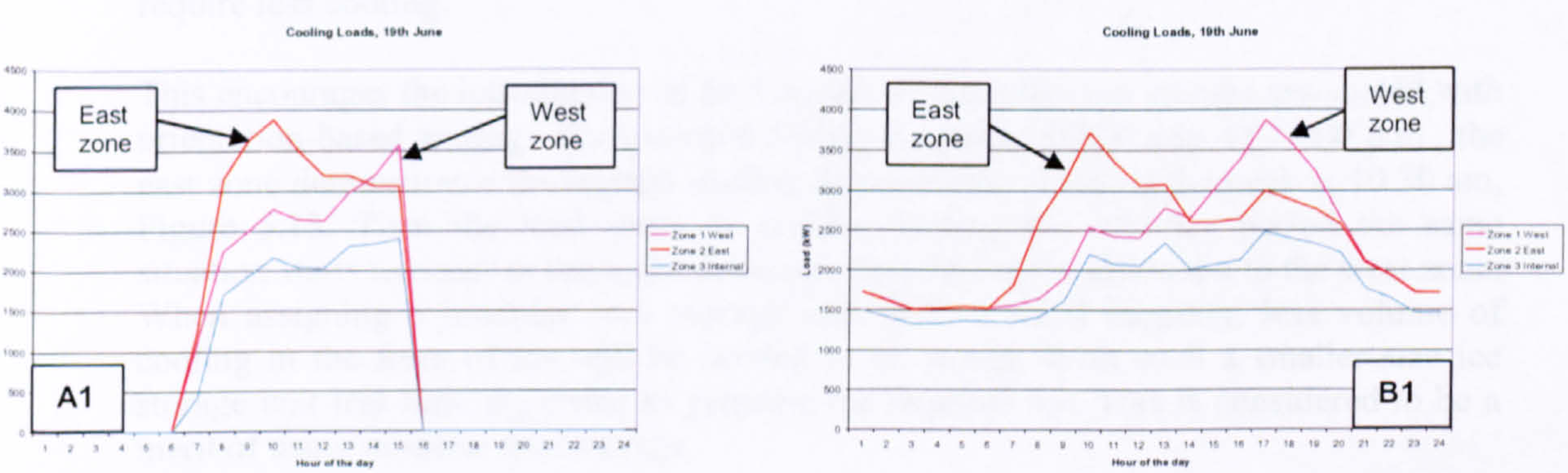

Figure 5.11 Load profiles for the long thin building representing a public building with offices having east and west orientations

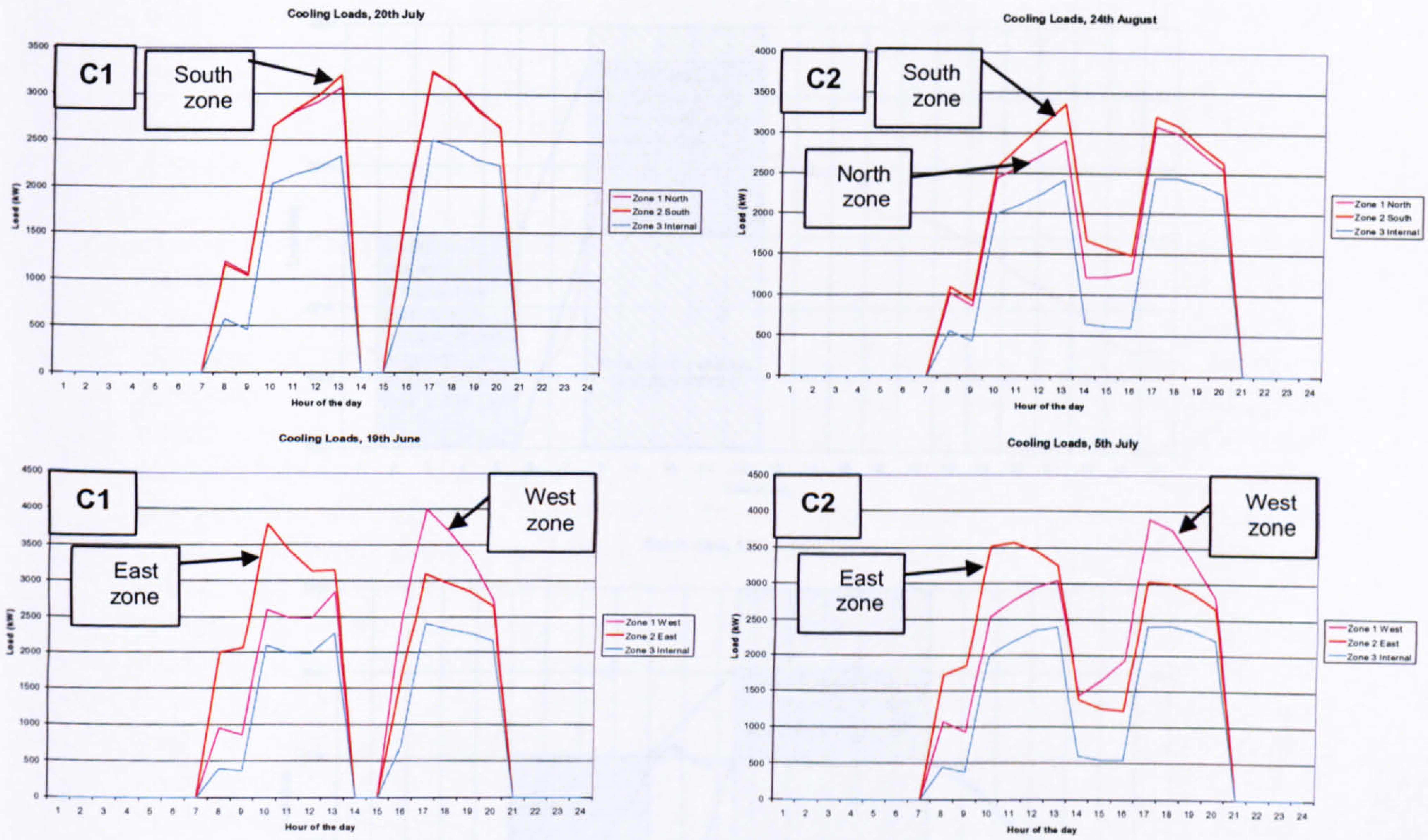

Figure 5.12 Cooling load profiles for a deep plan building representing a private sector office building, where A and B relate to the designated occupancy schemes

5.4.4 Suggested control zoning strategy

The load profiles of different zones have been derived from the computer simulations and demonstrated through figures 5.8, 5.9, 5.10, 5.11, and 5.12. The load profiles displayed independently in Figure 5.13 below represent east, south and west zones in the model simulated. These figures show how the load profile from one zone to another varies with time and that the time when a specific zone, the east zone for example, requires a specific amount of cooling other zones located at different orientations would require less cooling.

This encourages the introduction of the concept of modular cool storage associated with orientation-based zoning. For example during the period 09.00 a.m. to 12.00 p.m., the east zone demonstrates the highest cooling demand rate, reaching the peak at 10.30 am, Figure 5.13. Then the load starts to decline. During the mid-day period the same situation starts to occur in the south zone and then during the afternoon to the west zone. When assigning a modular cool storage unit, with a small capacity, less volume of cooling in the form of ice will be needed to be stored. With such a smaller size ice storage unit less time is needed to generate the required ice. This is considered to be a merit of using modular cool storage.

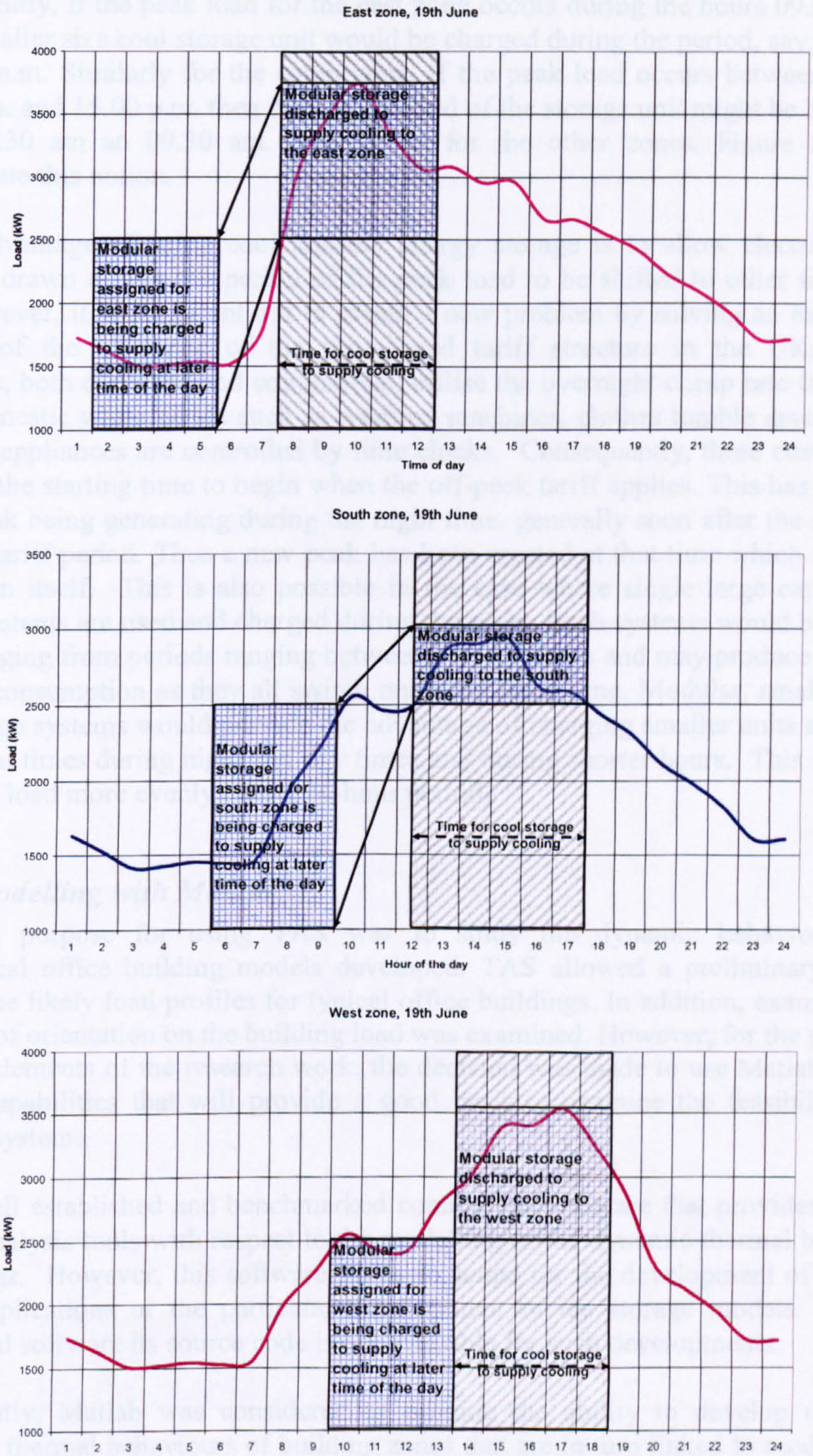

Figure 5.13 Profiles demonstrating opportunities for modular storage strategies

Consequently, if the peak load for the east zone occurs during the hours 09.00 to 12.00 then a smaller size cool storage unit would be charged during the period, say, 01.00 a.m. to 05.00 a.m. Similarly for the south zone, if the peak load occurs between the hours 12.30 p.m. and 15.00 p.m. then charging period of the storage unit might be between the hours 05.30 am an 09.30 am. And so on for the other zones. Figure 5.13 above demonstrate this notion.

A key advantage of using cool thermal energy storage is to allow electrical energy normally drawn during the period of the peak load to be shifted to other times of the day. However, it is important not to create a new problem by solving an existing one. Because of the existence of the time-based tariff structure in the UK, many of customers, both domestic and commercial, utilise the overnight cheap rate tariff. Most of the domestic white goods such as washing machines, clothes tumble dryers or other electrical appliances are controlled by time clocks. Consequently, these customers can postpone the starting time to begin when the off-peak tariff applies. This has resulted in a new peak being generating during the night time, generally soon after the start of the off-peak tariff period. Thus a new peak has been created at that time which might be a problem in itself. This is also possible in the case where single large capacity cool storage systems are used and charged during the night. Such systems would be expected to be charging from periods ranging between 7 to 12 hours and may produce secondary peaks of consumption as they all switch on at the same time. Modular, small capacity, cool storage systems would provide the advantage of charging smaller units at a variety of different times during night and day times and during shorter hours. This is likely to spread the load more evenly over a 24-hour period.

5.4.5 Modelling with Matlab

The main purpose for using TAS was to study the dynamic behaviour of the stereotypical office building models developed. TAS allowed a preliminary in-depth study of the likely load profiles for typical office buildings. In addition, examination of the effect of orientation on the building load was examined. However, for the purpose of the main elements of the research work, the decision was made to use Matlab software with its capabilities that will provide a good basis to examine the feasibility of the proposed system.

TAS is well established and benchmarked commercial software that provides different types of analysis tools with respect to the modelling of the dynamic thermal behaviours of buildings. However, this software gives no scope for the development of specialist control applications or the particular development of ice storage models. As it is commercial software its source code is not available for such developments.

Consequently, Matlab was considered to provide the ability to develop models to predict the thermal behaviours of building zones that are in turn linked to models of the components of building services systems and their associated controls. This gives a broader base for studying all the subsystems under the umbrella of a one complete model. Matlab also is a popular tool with a wide base of users in many academic institutions worldwide. It was considered that the Matlab model could be validated by comparing its predictions for free running conditions against those provide by the benchmarked commercial software TAS.

A previous Matlab model built by Lugg (1999) was utilised as the starting point for the development of this project. Lugg's model was initially built to examine the feasibility of a fuzzy logic controller to maintain acceptable conditions of thermal comfort in UK office buildings for minimum energy and cost expenditures. Major modifications were required to be able to utilise the model for the purpose of this research work. The model presented in this work has different dimensions than the model originally created by Lugg. The total solar radiation incident on a vertical surface used equation for a cloudy day. In the case of the new building model, the assumption for solar radiation modelling was made that the sky is clear and no clouds exist. This required that the radiation model was re-written to account for a clear sky day. Additionally the weather model was changed to represent a typical year for Kuwait.

Other input variables such as properties of building materials, building orientation and internal gains from occupants and equipment had to be defined and input into the Matlab model. A major aspect of the new model was the development of the HVAC systems model. Considerable instabilities occurred in relation to the cooling circuit of this system and much time was taken in the sizing of the cooling heat exchanger and its interaction with the associated chillers and conventional controllers to ensure stable functioning of the simulation model.

5.4.6 The building model

Buildings and building systems modelling and simulation is complex, especially when the process of modelling involves simulating the total building envelope and the associated building services systems such as the Heating, Ventilation and Air Conditioning (HVAC) system.

For this research it was considered that the best approach would be to develop a single zone model as being representative of an entire office building. The single zone unit had the same dimensions as for the TAS model with a length of 6 meters, width of 6 meters and height of 3 meters.

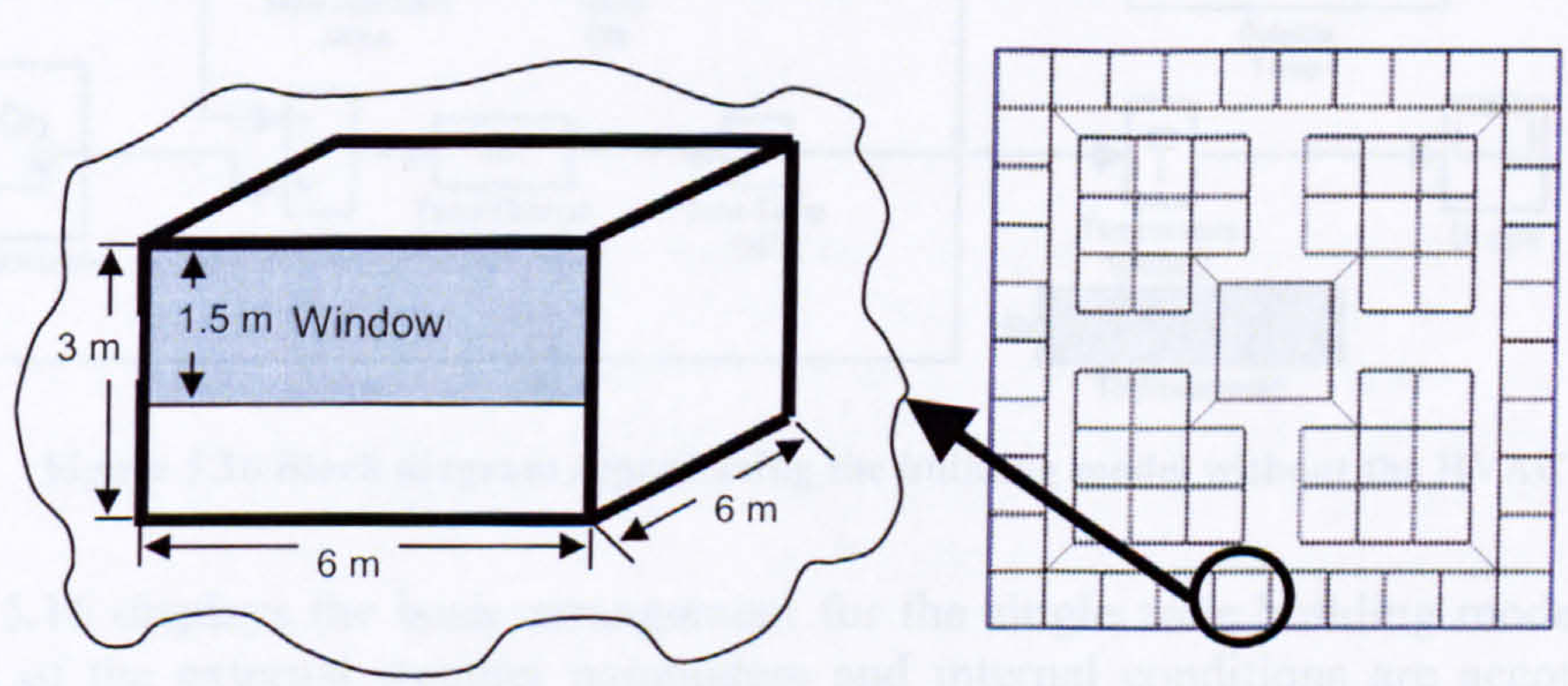

Figure 5.14 Layout of the single zone model

The model comprised the building represented by the single zonal unit and the associated HVAC plant. The unit cell model includes the different dynamic heat transfer interactions between the envelope and internal construction elements and the key weather parameters, figure 5.15. It also deals with the internal gains inside the zone such as gains from occupants, lighting and machines.

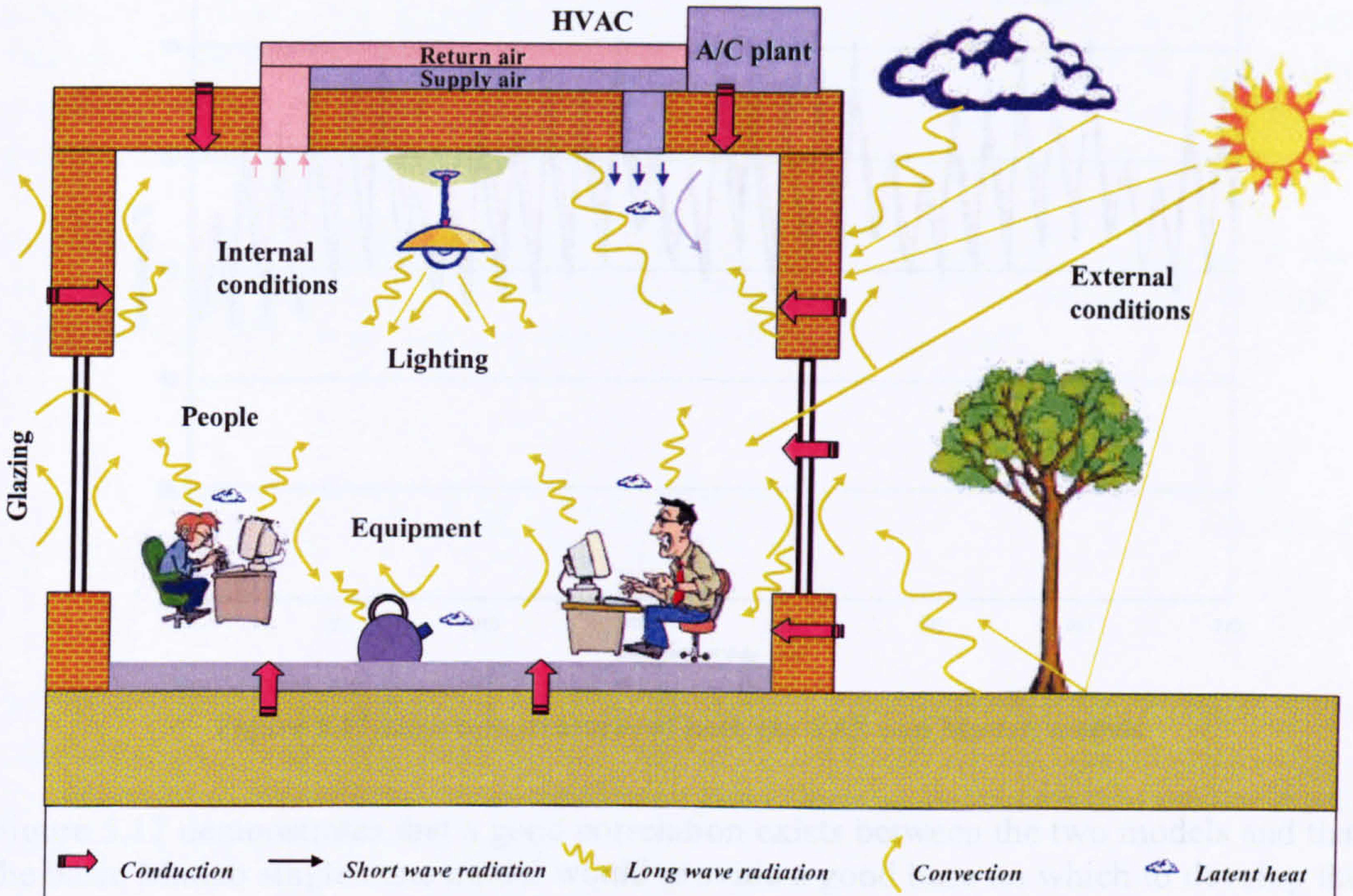

Figure 5.15 Means of heat transfer in buildings

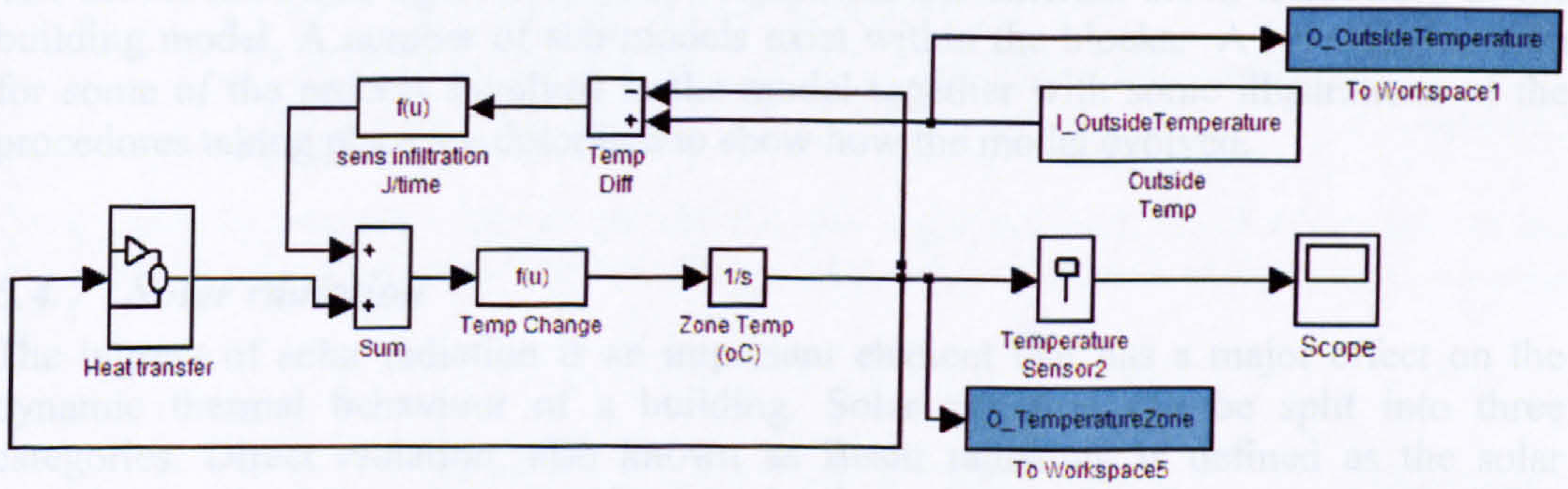

Figure 5.16 Block diagram representing the building model without the HVAC

Figure 5.16 displays the basic arrangement for the single zone building model. In this part all of the external weather parameters and internal conditions are accounted for within the various "boxes" shown in the figure. The main output that will be communicated to the HVAC control is the temperature predicted for the zone. A plot of the zone temperature for the Matlab model for a free running condition, i.e. no cooling or heating was provided by the HVAC system, was compared with the zone temperature of the same basic zone model that was built in TAS. The aim of this comparison was to test the output of the Matlab model against that of the benchmarked TAS software.

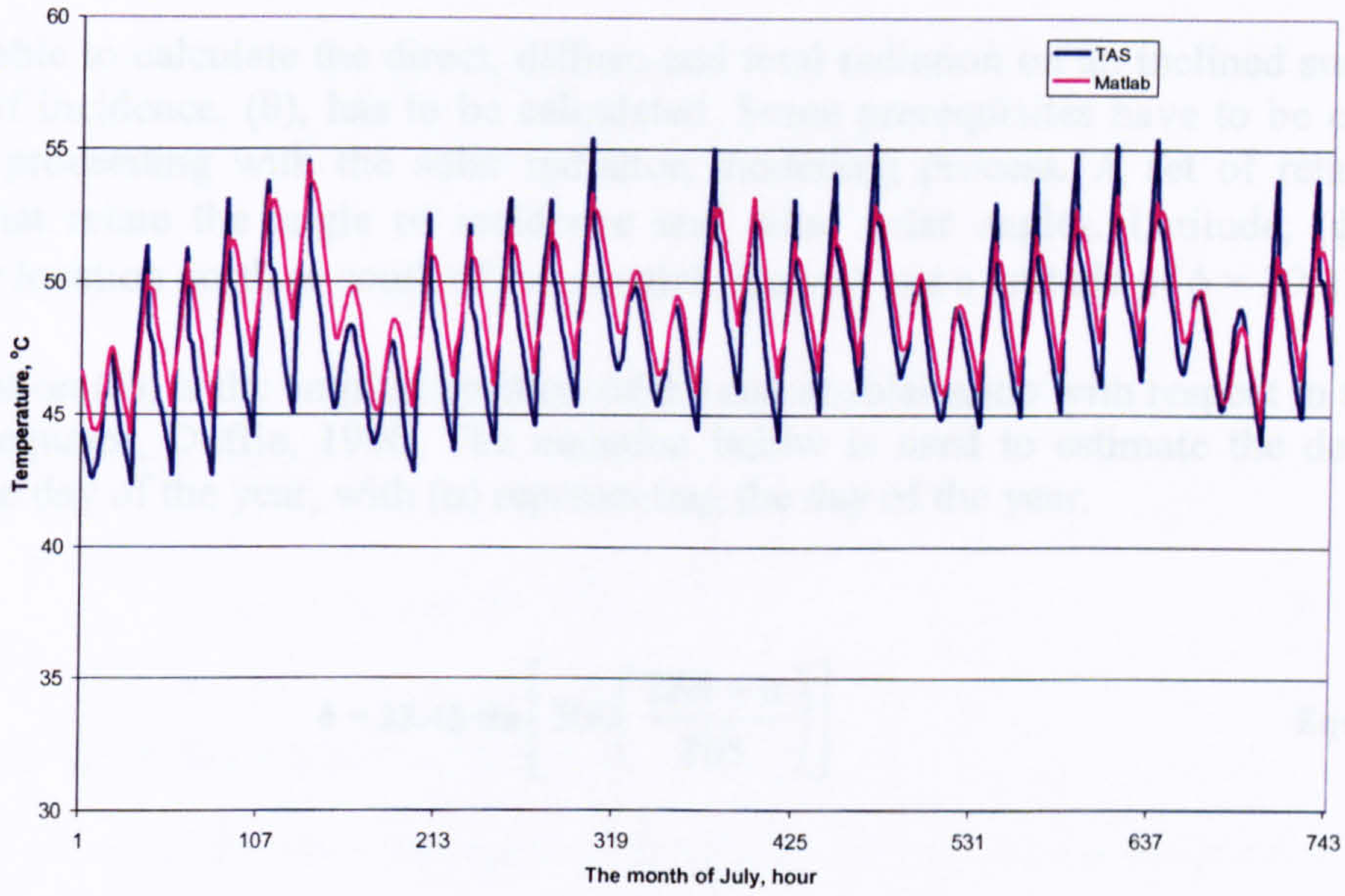

Figure 5.17 Zone temperatures of both the TAS and Matlab models

Figure 5.17 demonstrates that a good correlation exists between the two models and that the basic Matlab single zone model would provide a good base on which to develop the HVAC system and the control system models. The month of July was chosen as the extremes of the weather conditions occur during this month. The difference in the zone temperature between the TAS and Matlab models ranged between 0°C to 2.6°C.

The model shown in figure 5.16 above represents the external block framework of the building model. A number of sub-models exist within the blocks. A brief explanation for some of the process involved in the model together with some illustrations of the procedures taking place are described to show how the model evolved.

5.4.7 Solar radiation

The ingress of solar radiation is an important element that has a major effect on the dynamic thermal behaviour of a building. Solar radiation can be split into three categories. Direct radiation, also known as Beam radiation, is defined as the solar radiation received from the sun without having been scattered by the atmosphere, Duffie 1990. Diffuse or sky radiation, is the solar radiation received from the sun after its direction has been changed by scattering within the atmosphere. The sum of beam and diffuse solar radiation components falling on a surface is identified as total radiation, also known as global radiation.

The rate of incidence of solar radiation for horizontal surfaces can usually be found in a weather databases in the form of global and diffuse solar radiation. In the case of the single zone model, an external wall with a window area was defined. Calculations were applied to determine values of solar radiation incident on the vertical wall and glass surfaces.

To be able to calculate the direct, diffuse and total radiation on an inclined surface, the angle of incidence, (θ), has to be calculated. Some prerequisites have to be calculated before proceeding with the solar radiation modelling process. A set of relationships exist that relate the angle of incidence and other solar angles. Latitude, (ϕ), is the angular location north or south of the equator. Kuwait has a latitude of $\phi = 29.33°$.

Declination (δ), is the angular position of the sun at solar noon with respect to the plane of the equator, Duffie, 1990. The equation below is used to estimate the declination from the day of the year, with (n) representing the day of the year.

$$\delta = 23.45 \sin\left[360\left(\frac{284+n}{365}\right)\right] \qquad \textbf{Equation 5.1}$$

The external wall and window are vertical surfaces. For vertical surfaces the value of the surface slope $\beta = 90°$, Duffie, 1990. The building in the model could be assumed to be orientated in any direction but for this explanation is assumed to be facing south, this results in a surface azimuth angle of $\gamma = 90°$.

Once all the values of the solar angles are calculated, the angle of incidence can be calculated from

$$\begin{aligned}\cos\theta &= \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma \\ &+ \cos\delta \cos\phi \cos\beta \cos\omega \quad + \cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega \\ &+ \cos\delta \sin\beta \sin\gamma \sin\omega\end{aligned} \qquad \textbf{Equation 5.2}$$

To be able to proceed with the calculation, the angle between the direct radiation and the normal to the horizontal surface, Zenith angle (θ_z), must also be calculated, equation 5.3.

$$\cos\theta_z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta \qquad \textbf{Equation 5.3}$$

The rate of incidence of solar radiation on the vertical wall be calculated from the value of the ratio of beam radiation on the tilted surface to that on a horizontal surface, the value obtainable from measured weather data. The ratio is given by

$$R_b = \frac{\cos\theta}{\cos\theta z}$$ **Equation 5.4**

Then, direct solar radiation can be calculated from

$$I_{Idirect} = I_{Hdirect} * R_b$$ **Equation 5.5**

5.4.8 Diffuse Solar Radiation on a Vertical surface

The diffuse component is assumed to be isotropically distributed and can be calculated from the following equation

$$I_{Idiffuse} = I_{Hdiffuse} \cos^2(\beta)$$ **Equation 5.6**

5.4.9 Ground Reflected Radiation

This is a function of surface tilt, the rate of diffuse solar radiation incident on a horizontal surface and the ground reflectance. The value of the ground reflected radiation incident on an inclined surface can be calculated using the following equation

$$I_{Igref} = \rho_g I_{Htotal} \sin^2(\beta/2)$$ **Equation 5.7**

The ground reflectance, ρ_g, typically has a value of 0.2 for soil.

5.4.10 Total Radiation Incident on an inclined surface

For the purpose of the one zone model under development, it was assumed that the sky is clear and the radiation is isotropically distributed. The following equation was used for the calculation

$$I_{Itotal} = I_{Igref} + R_b (I_{Hdiffuse} + I_{Hdirect})$$ **Equation 5.8**

5.4.11 Solar Radiation Transmission through Glass

For vertical surfaces the equivalent angle of incidence for diffuse and ground reflected radiation is 60°, Duffie 1990. For radiation incident at 60° the transmittance through glass is equal to 50% of the total. Applying this value allows diffuse and ground reflected radiation to be treated as direct radiation.

Transmission of direct radiation through glass is dependent on the angle of incidence of the radiation with the glass surface. The relationship between the angle of incidence of the beam radiation and the glass transmissivity and surface reflectivity is described by Snell's law

$$\text{Sin } \theta_t = \frac{\sin\theta}{n} \qquad \textbf{Equation 5.9}$$

n is the refractive index and has a value of 1.52.

Figure 5.18 shows a schematic of the path of direct (Beam) radiation through a sheet of glass and the associated nomenclature for the angles. The transmittance for each of the two surfaces is given by the Fresnel equations for polarisation perpendicular and parallel to the plane of incidence using **equation 5.10** to define the ratio of the transmission angle to the angle of incidence, see **equation 5.11** and **equation 5.12**, EDSL.

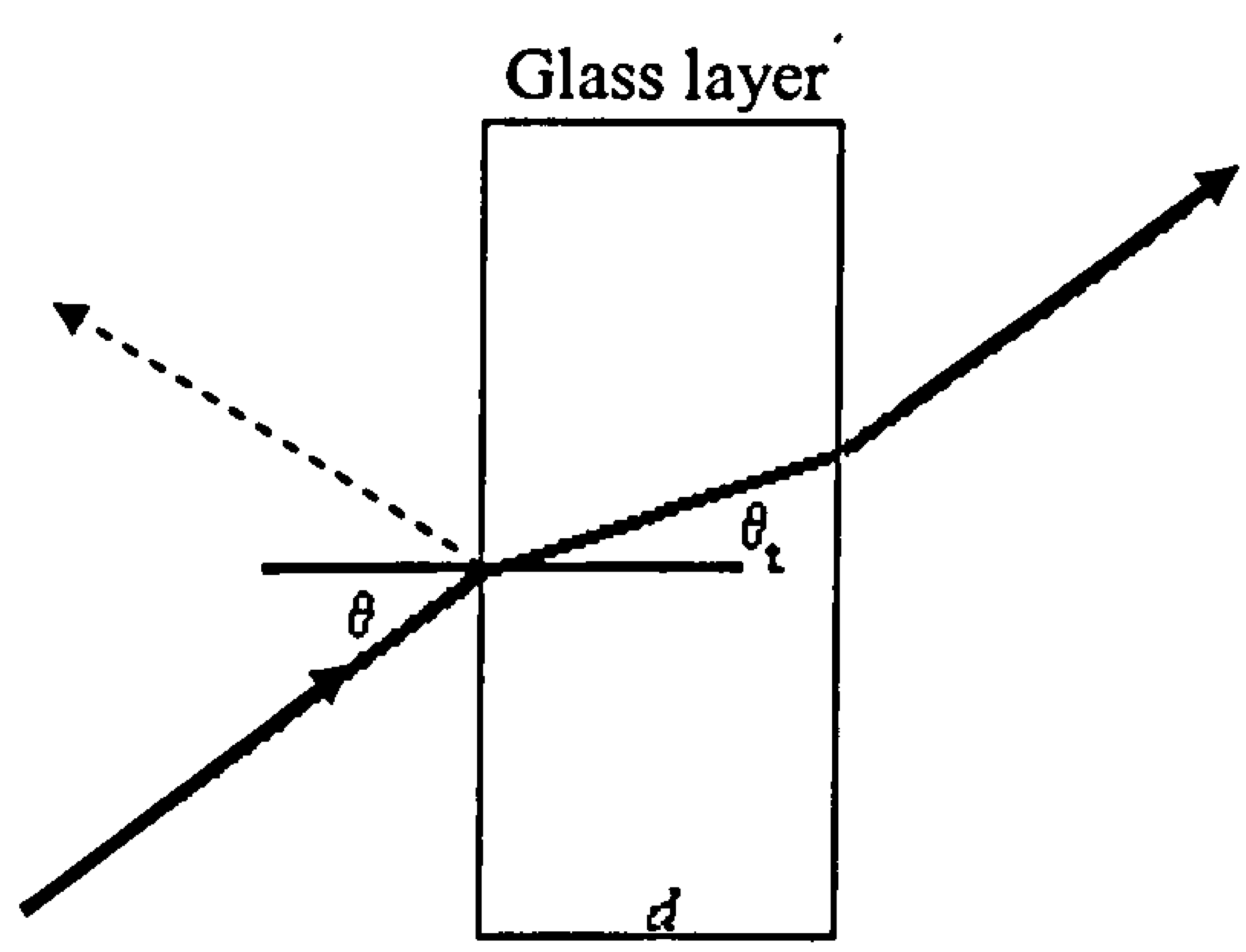

Figure 5.18 Transmission through a single-layer transparent construction

$$c(\theta) = \frac{\cos(\theta_t)}{\cos(\theta)} \qquad \textbf{Equation 5.10}$$

$$t_{perp} = \frac{4n.c(\theta)}{(1+n.c(\theta))^2} \qquad \textbf{Equation 5.11}$$

$$t_{para} = \frac{4n.c(\theta)}{(n + c(\theta))^2}$$ **Equation 5.12**

If the layer is absorbing, the factor by which the ray is attenuated on passing through is described by **equation 5.13.**

$$b(\theta) = \exp\left(\frac{-x_c d}{\cos(\theta_t)}\right)$$ **Equation 5.13**

By setting θ to zero, i.e. normal incidence, and rearranging **equation 5.13** the result is given by **equation 5.18**. The "o" subscript in **equation 5.14** to **equation 5.17** denotes evaluation at θ = 0.

$$b(0) = b_o^{\frac{1}{\cos(\theta_t)}}$$ **Equation 5.14**

Equation 5.16 and **equation 5.17** is another way to calculate b_o

$$b_o \cong \left(\frac{\tau_o}{\tau_o^2}\right)\left(1 - \frac{\tau_o r_o^2}{t_o^4} + \frac{2\tau_o^4 r_o^4}{t_o^8}\right)$$ **Equation 5.15**

where

$$t_o = \frac{4n}{(n+1)^2}$$ **Equation 5.16**

$$r_o = 1 - t_o$$ **Equation 5.17**

Analysis of an infinite number of internal reflections, EDSL shows that the transmittance of the complete layer, for the two polarisations, is given by **equation 5.16** and **equation 5.17**, and the use of **equation 5.18** and **equation 5.19**.

$$\tau_{perp} = \frac{bt_{perp}^2}{(1 - r_{perp}^2 b^2)}$$ **Equation 5.18**

$$\tau_{para} = \frac{bt_{para}^2}{(1 - r_{para}^2 b^2)}$$ **Equation 5.19**

where

$$r_{perp} = 1 - t_{perp}$$ **Equation 5.20**

$$r_{para} = 1 - t_{para}$$ **Equation 5.21**

The transmittance of the layer for randomly polarised radiation is found by averaging the two polarisations, see **equation 5.22.**

$$\tau(\theta) = \frac{\tau_{perp}(\theta) + \tau_{para}(\theta)}{2}$$ **Equation 5.22**

The model assumes that the direct and diffuse solar radiation which passes through the glazing is distributed over the interior surfaces of the zone on an area weighted basis. It is also assumed that 88% of the energy is absorbed by the walls and 12% is reflected back out of the window, Duffie (1990).

5.4.12 A transient one-dimensional finite difference heat transfer model for the external wall (The explicit method)

A numerical solution is necessary to account for the time dependent transient conduction occurring in the walls and window. Assuming all heat transfer is into the element, an energy balance on the element may be expressed as

Energy flow rate into the element, E_{in}	+	Heat generated within the element, E_g	=	Rate of change of internal energy, E_{st}

A numerical solution is obtained by partitioning the building element into several segments. Taking as an example the case for the external wall where it was partitioned into four segments, figure 5.19.

A set of several equations is created. Each equation deals with calculating the temperature for the node under consideration. To reflect the logic behind developing the nodal equations, the procedure towards developing the nodal equations at T_1 and T_2 is explained.

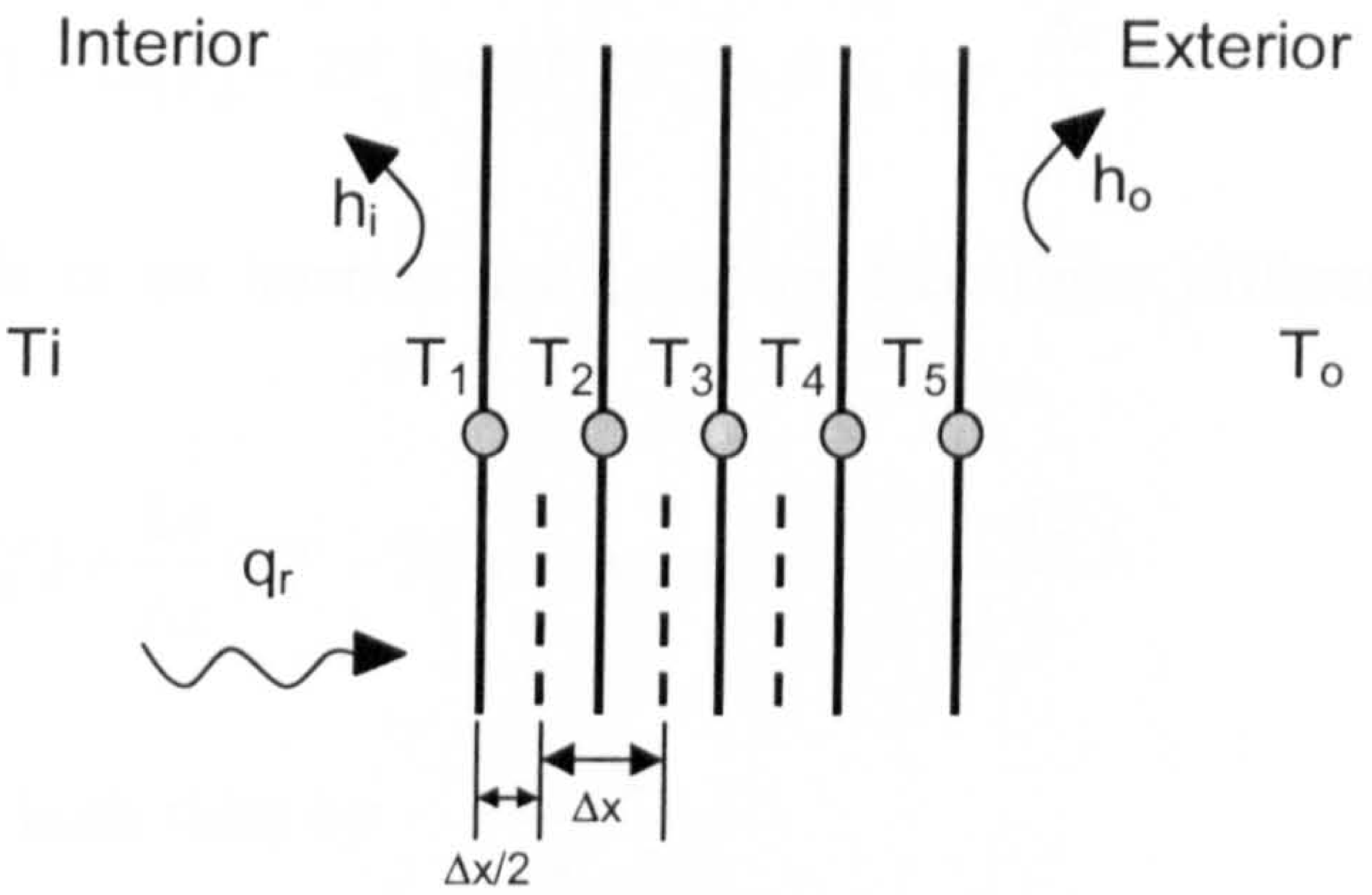

Figure 5.19 External wall representation with the segments and nodes

From figure 5.19, T_1 and T_5 are considered as external nodes. T_2, T_3 and T_4 are considered as internal nodes. T_1 is an external node at the external surface of the wall. It is a boundary node subjected to convection, and the finite difference formulation at that node is obtained by writing an energy balance on the volume element of thickness Δx/2 at that boundary by assuming heat transfer to be into the medium at all sides

$$h_i A(T_i - T_1^p) + \frac{kA}{\Delta x}(T_2^p - T_1^p) + q_r A = \rho c_p A \frac{\Delta x}{2} \frac{(T_1^{p+1} - T_1^p)}{\Delta t}$$

multiplying both sides by $\frac{2\Delta t}{\rho c_p A \Delta x}$

$$\frac{2h_i \Delta t}{\rho c_p \Delta x}(T_i - T_1^p) + \frac{2k\Delta t}{\rho c_p (\Delta x)^2}(T_2^p - T_1^p) + \frac{2\Delta t}{\rho c_p \Delta x} q_r = (T_1^{p+1} - T_1^p)$$

the Biot number $B_i = \frac{h\Delta x}{k}$, and Fourier number $F_o = \frac{k\Delta t}{\rho c_p (\Delta x)^2} = \frac{\alpha \Delta t}{(\Delta x)^2}$

(α) is the thermal diffusivity

$$\frac{2h_i \Delta t}{\rho c_p \Delta x} = 2 * (\frac{h\Delta x}{k}) * (\frac{k\Delta t}{\rho c_p (\Delta x)^2}) = 2 * B_i * F_o$$

$$T_1^{p+1} = \frac{2h_i \Delta t}{\rho c_p \Delta x}(T_i - T_1^p) + \frac{2k\Delta t}{\rho c_p (\Delta x)^2}(T_2^p - T_1^p) + \frac{2\Delta t}{\rho c_p \Delta x} q_r + T_1^p$$

$$T_1^{p+1} = 2\mathrm{B_i} F_o T_i - 2\mathrm{B_i} F_o T_1^p + 2F_o T_2^p - 2F_o T_1^p + 2F_o (q_r \frac{\Delta x}{k}) + T_1^p$$

$$T_1^{p+1} = T_1^p(1-2b_iF_o-2F_o)+2F_o(T_2^p+B_iT_i+q_r\frac{\Delta x}{k})$$

For node 2, which is an interior node, the explicit finite difference formulation is obtained below

$$\frac{kA}{\Delta x}(T_1^p-T_2^p)+\frac{kA}{\Delta x}(T_3^p-T_2^p)=\rho c_pA\Delta x\frac{(T_2^{p+1}-T_2^p)}{\Delta t}$$

multiplying both sides by $\dfrac{\Delta t}{\rho c_p A\Delta x}$

$$\frac{k\Delta t}{\rho c_p(\Delta x)^2}(T_1^p-T_2^p)+\frac{k\Delta t}{\rho c_p(\Delta x)^2}(T_3^p-T_2^p)=T_2^{p+1}-T_2^p$$

Fourier number $F_o = \dfrac{k\Delta t}{\rho c_p(\Delta x)^2}=\dfrac{\alpha\Delta t}{(\Delta x)^2}$

(α) is the thermal diffusivity

$$T_2^{p+1}=F_oT_1^p-F_oT_2^p+F_oT_3^p-F_oT_2^p+T_2^p$$

$$T_2^{p+1}=T_2^p(1-F_o)+F_o(T_1^p+T_3^p)$$

The same procedures are applied for nodes 3 and 4.

The solar radiation model and the transient conduction through the wall model have been shown as examples of components of the dynamic building model contained within the Matlab block framework.

5.4.13 Building model with HVAC

To simulate the performance of an HVAC system, it was necessary to understand the performance characteristics of the components used in the system. An HVAC system is required to provide heating, cooling, humidity control and ventilation to the various zones in a building to satisfy the thermal comfort and air quality conditions required in buildings. This implies complex interactions between the systems and the behaviours of the building and its occupants.

The model represented in figure 5.20 is a conventional air conditioning system in a building that would consist of an air handling unit(s) (AHU), which contains the cooling coil and the dampers that provide flow control. Chilled water with a fixed temperature of 5°C was assumed to be flowing from the chiller to the cooling coil in the AHU.

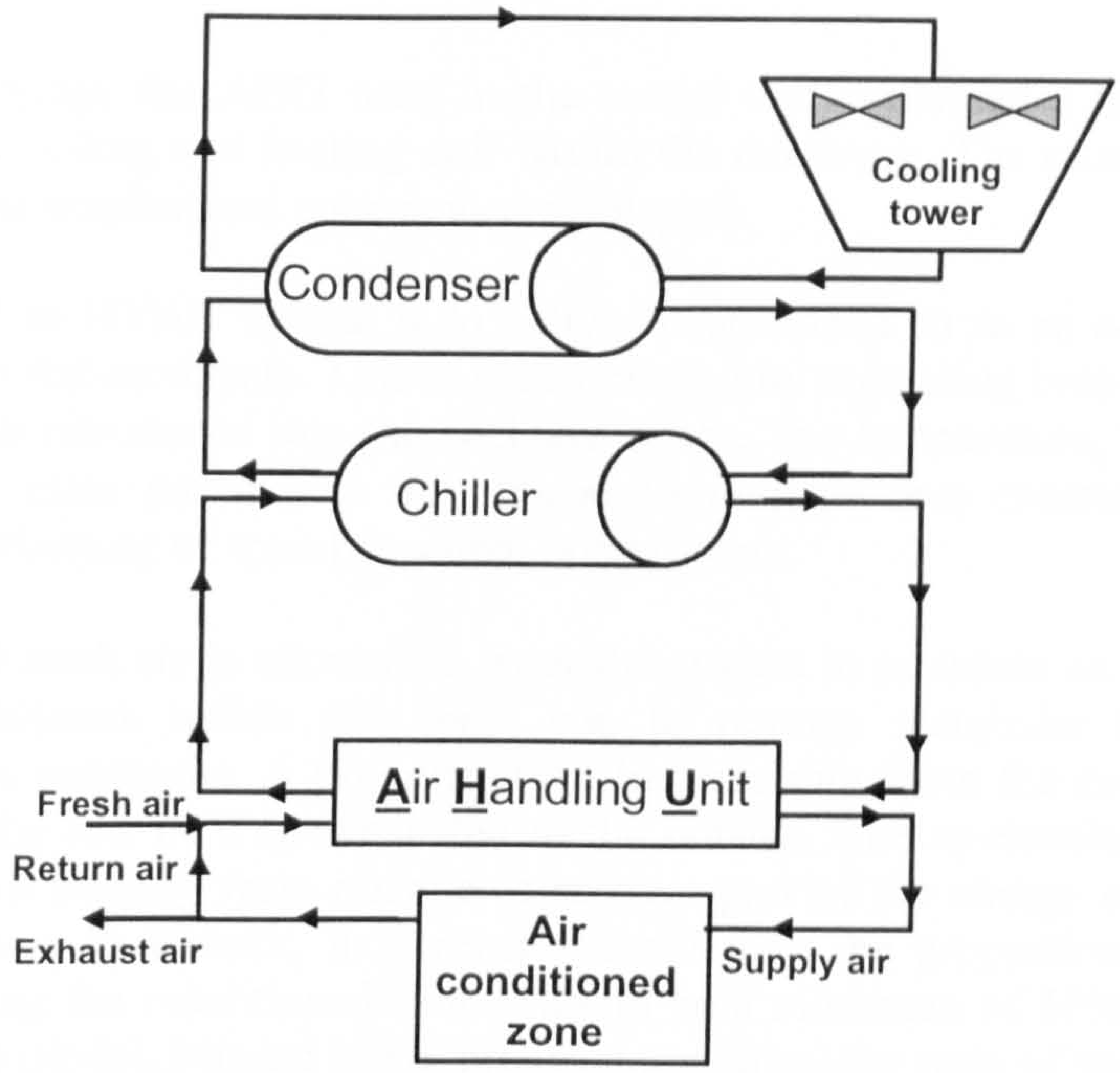

Figure 5.20 A conventional type of air conditioning system in an office building

The air handling unit (AHU) represented the HVAC part of the model. Figure 5.21 shows a detailed schematic of an AHU with its components.

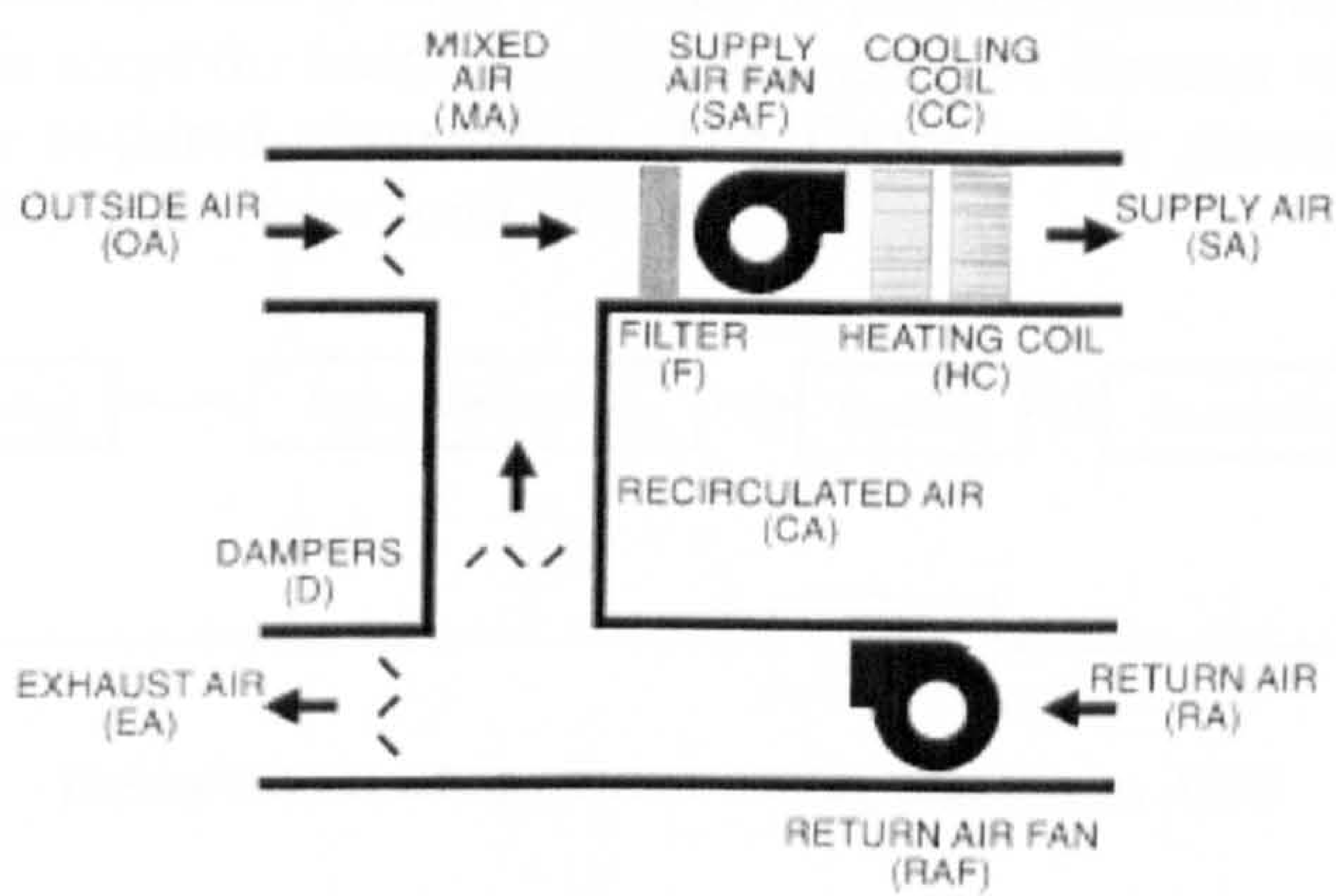

Figure 5.21 Schematic of the HVAC system, (ASHRAE 2001)

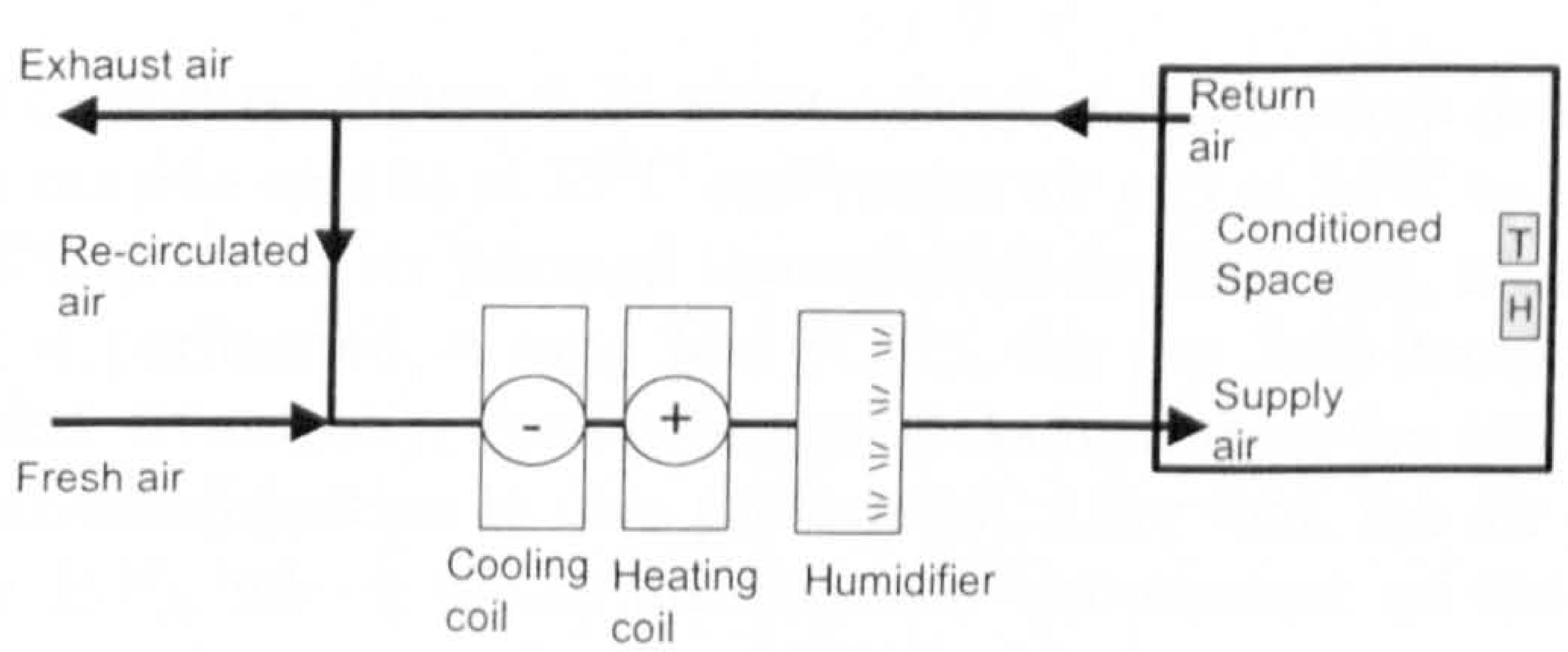

Figure 5.22 Schematic showing an air conditioned space with the HVAC components

Figure 5.22 displays the AHU used in the model that contained a humidifier unit in addition to the cooling and heating coil within the ductwork. The relationship between the AHU and the conditioned zone is also displayed.

The purpose of an HVAC system is to deliver conditioned air to an occupied space to provide comfort for occupants. This is accomplished by regulating both the quantity and quality of the air introduced into the enclosed space. The temperature, humidity and air quality are the main parameters the air-conditioning process controls and regulates through the functioning of specific system components.

A proportion of fresh air is allowed to enter the system to maintain an acceptable level of healthy conditions within the zone, e.g. to remove metabolic CO_2 and odour produced by the occupants. A proportion of the return air from the zone extract is re-circulated and the rest of it is exhausted to the outside. The re-circulated air is mixed with the fresh air coming from outside to recover part of the energy coming from the conditioned space. In Kuwait, it is recommended that the proportion of fresh air to return air entering the conditioned space should be a minimum of 10%, and this value was used for the model. Mixing boxes are used to control the ratio of the zone return air to fresh outside air that is supplied to the zone via the AHU.

In addition to the cooling function of the cooling coil, the air may become further cooled during the dehumidification process to condense out excessive water vapour contained in the inlet air. As the process of dehumidification occur the conditioned air temperature may become lower than required to provide comfortably the desired zone temperature. At this stage the heating coil acts as a reheat element where it raises the air temperature to the required temperature. The figure below presents the flow of the process from a building services point of view.

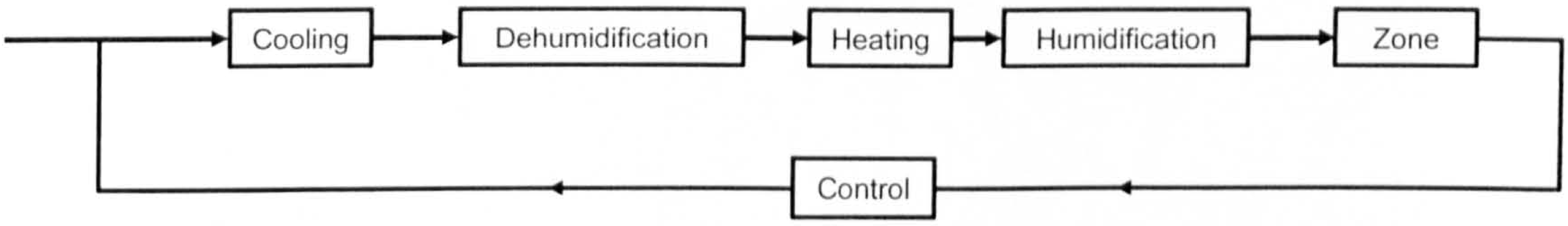

Figure 5.23 Cooling process taking place in an AHU

The system above relates to the complete equipment suite and humidification and dehumidification should not both be functioning at the same time for efficient operation.

The psychometric chart on figure 5.24 shows the thermodynamic processes that occur when mixing the outside air (B) at 35°C and return air (A) at 24°C to create a mixed air stream (C) at 26°C prior to its passage through the cooling coil, along line (C-E). As sensible cooling is performed, a long line (C-E), the dry bulb temperature of the air stream is decreased. Eventually, the cooling process intersects the saturation curve (D), at which point dehumidification is also performed. After that, the air passes through a re-heat coil, line E-F), which raises the sensible temperature of the supply air. The supply air then enters the space, where sensible and latent heat are transferred from the space to the air-stream. Finally, the return air leaves the space (A), to be mixed with fresh outdoor air, re-starting the HVAC cycle.

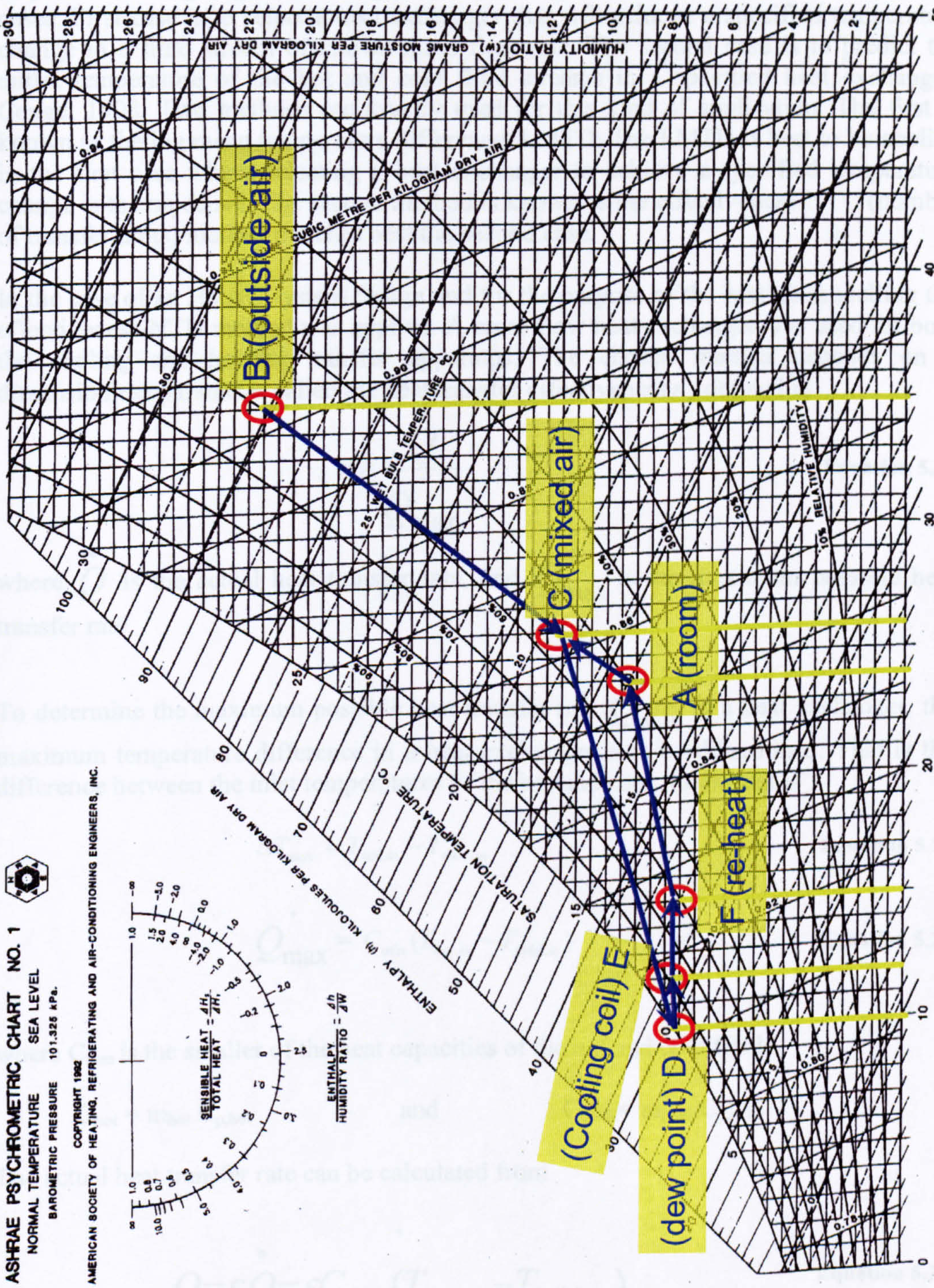

Figure 5.24 The complete HVAC cycle demonstrated on the psychometric chart

5.4.14 Cooling coil design

A cooling coil is one type of the many types of heat exchangers that are commonly used in practice. Designing or selecting a heat exchanger should be referred to one of two cases. First case is to select a heat exchanger that will achieve a specified temperature change in a fluid stream of known mass flow rate. The second case is to predict the outlet temperature of the hot and cold fluid streams in a specified heat exchanger, Cengel 1998. Two methods are usually used for this kind of application. The first is known as the log mean temperature difference, LMTD. The LMTD is best to be applied in the first case where selecting a heat exchanger to achieve a specified temperature change is the objective. The second method is known as the effectiveness-NTU (number of transfer units) method matches best the second case.

In the case of an HVAC system design and for the purpose of the Matlab modelling the effectiveness-NTU method was applied. A cross flow heat exchanger was used for both the cooling and heating transfer apparatus. The chosen method depends on a dimensionless parameter called the heat transfer effectiveness ε, defined as

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} \qquad \textbf{Equation 5.23}$$

where $\dot{Q}$ is the actual heat transfer rate, and $\dot{Q}_{\max}$ is the maximum possible heat transfer rate.

To determine the maximum possible heat transfer rate $\dot{Q}_{\max}$ in a heat exchanger, the maximum temperature difference in a heat exchanger is to be determined. That is the difference between the inlet temperatures of the hot and cold fluids, that is

$$\Delta T_{\max} = T_{hot,in} - T_{cold,in} \qquad \textbf{Equation 5.24}$$

$$\dot{Q}_{\max} = C_{\min}(T_{hot,in} - T_{cold,in}) \qquad \textbf{Equation 5.25}$$

where C_{min} is the smaller of the heat capacities of the hot and cold fluids

$C_{hot} = m_{hot}\, C_{p,hot}$ and $C_{cold} = m_{cold}\, C_{p,cold}$

The actual heat transfer rate can be calculated from

$$\dot{Q} = \varepsilon \dot{Q} = \varepsilon C_{\min}(T_{hot,in} - T_{cold,in}) \qquad \textbf{Equation 5.26}$$

The effectiveness relation for a single pass cross flow heat exchanger, with both fluids unmixed, used for the Matlab model is given by equation 5.27, Cengel 1998.

$$\varepsilon = 1 - \exp\left\{\frac{NTU^{0.22}}{C}\left[\exp(-C \times NTU^{0.78}) - 1\right]\right\}$$ **Equation 5.27**

$C=(C_{min}/C_{max})$

$$NTU = \frac{UA}{C_{\min}}$$ **Equation 5.28**

The outlet temperatures for the hot and cold fluids were determined from the energy balance equation below

$$q = \dot{m} c_p (T_{out} - T_{in})$$ **Equation 5.29**

$$T_{hot,out} = T_{hot,in} - \frac{q}{\dot{m}_{hot}\, c_{p,hot}}$$ **Equation 5.30**

$$T_{cold,out} = T_{cold,in} - \frac{q}{\dot{m}_{cold}\, c_{p,cold}}$$ **Equation 5.31**

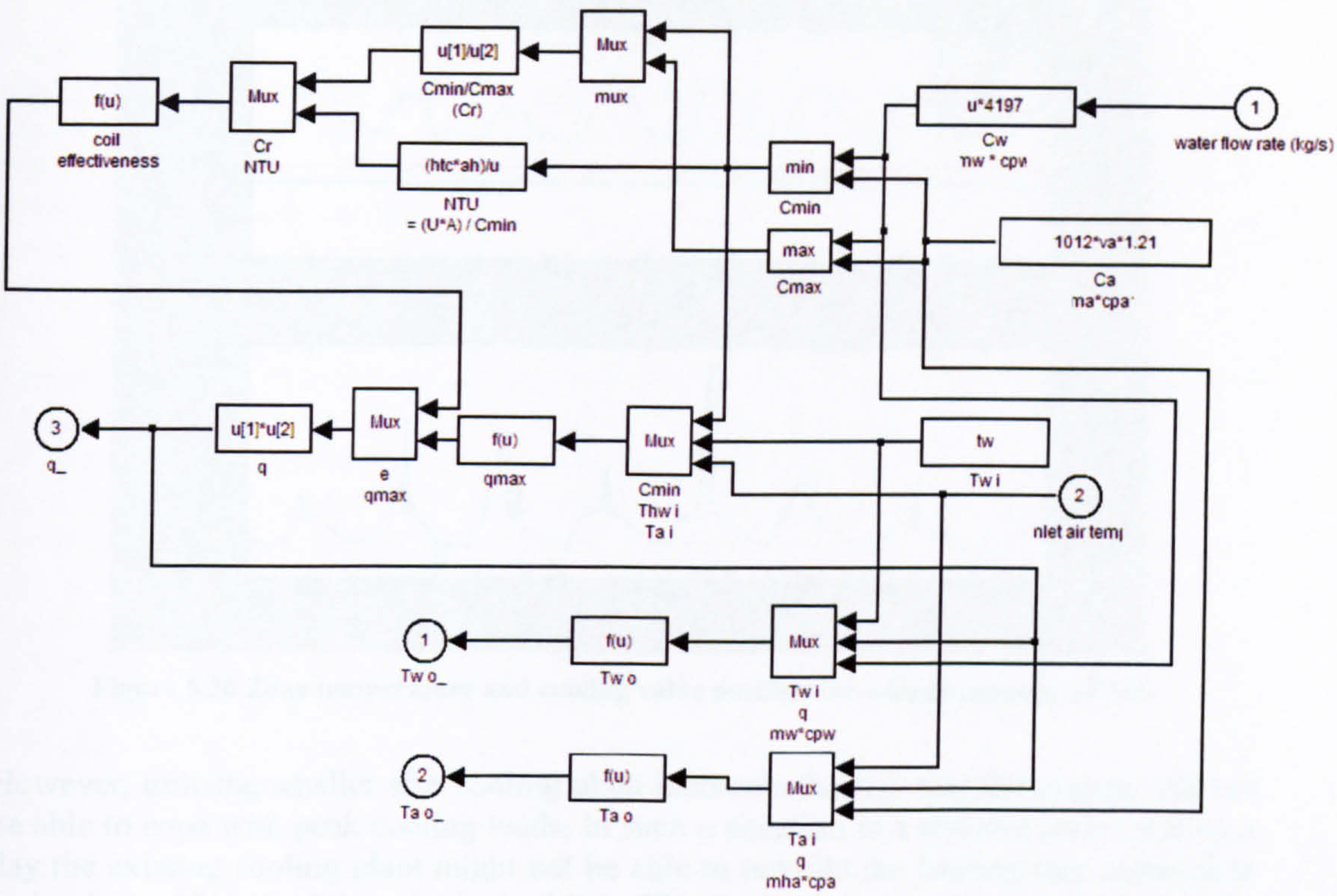

Figure 5.25 Schematic of the effectiveness-NTU method calculations used in Matlab as part of the HVAC systems model

In the case of the conventional design of HVAC systems the worst design day option generally is used to calculate a system capacity for heating and cooling that is able to achieve the conditions required within the building zone(s). This means having a system with large capacity that is able to supply the cooling or heating required for the respective worst day. However, the system will rarely operate at full load conditions. For the less severe periods of the season such a system will be operating on part load operation. In addition, the capital cost for a system with large capacity is high. Systems tend to operate less efficiently at part loads and seriously oversized systems utilise excessive energy at all periods except those when peak load conditions occur.

The consequences of oversized systems are illustrated in figure 5.26 by output from the Matlab model, which shows the ambient and room temperatures and the valve position for the chilled water flow to the cooling coil heat exchanger of the HVAC system for a series of days in the month of July. The upper part of the figure shows that the system is able to maintain the required zone temperature. The valve position representing the chilled water flow rate is shown in the lower part of the figure. It can be seen that the valve opens between 0 and 70% of the fully open position. This suggests an overcapacity of the chiller producing the chilled water and an oversized heat exchanger for the cooling coil.

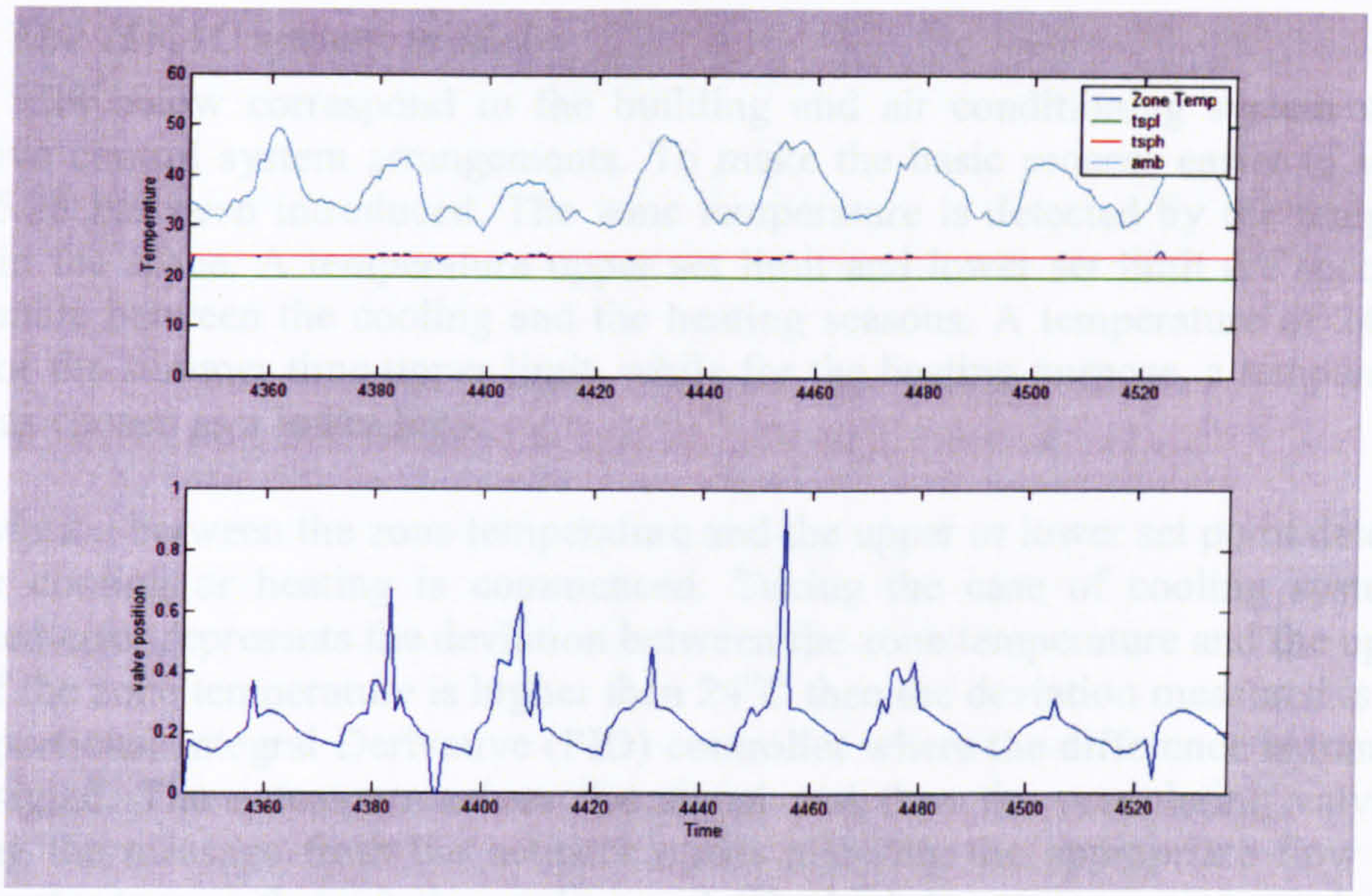

Figure 5.26 Zone temperature and cooling valve position for a large capacity HVAC

However, utilising smaller size cooling plant increases the risk that the system will not be able to cope with peak cooling loads. In such a situation at a specific period during a day the existing cooling plant might not be able to provide the cooling rate required to maintain comfort conditions in the building. This is illustrated in figure 5.27, where the peak of the zone temperature is above the zone set temperature. In addition, the lower part of the figure shows that the cooling valve is fully opening during most of the time during the mentioned period.

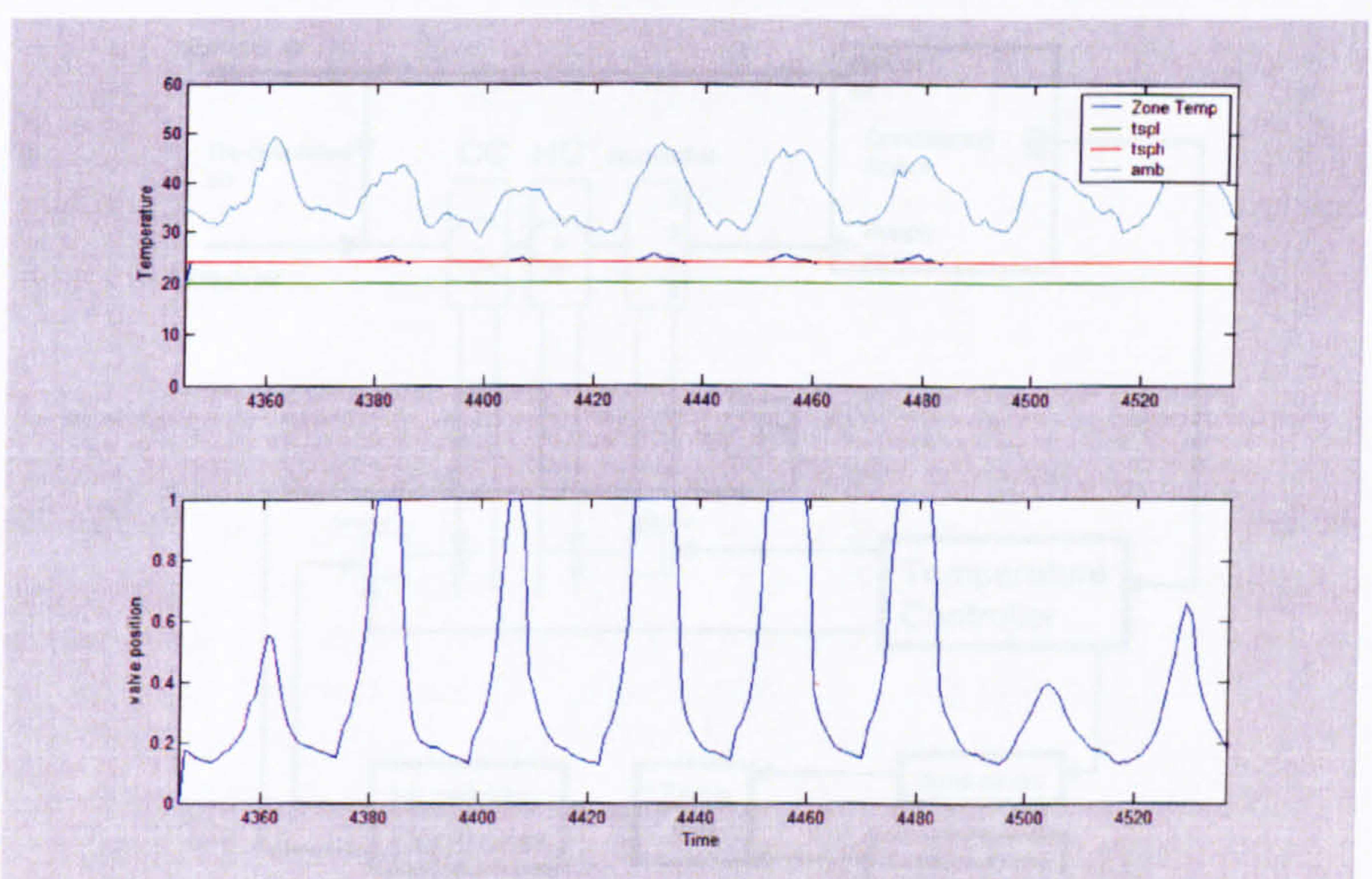

Figure 5.27 Zone temperature and cooling valve position for a small capacity HVAC

5.4.15 The HVAC system model

Figure 5.28 below correspond to the building and air conditioning system with the respective control system arrangements. To make the basic process easier to visualise figure 5.28 has been introduced. The zone temperature is detected by the temperature sensor in the space. A temperature upper set limit and lower set limit are specified to differentiate between the cooling and the heating seasons. A temperature of 24°C was set as for the summer time upper limit, while for the heating purpose, a temperature of 20°C was chosen as a lower limit.

The deviation between the zone temperature and the upper or lower set point determines whether cooling or heating is commenced. Taking the case of cooling system, the calculated error represents the deviation between the zone temperature and the upper set point. If the zone temperature is higher than 24°C then the deviation measured is sent to the Proportional Integral Derivative (PID) controller where the difference is transferred into a signal. The actuator receives the signal and then the modulating valve upon receiving the message from the actuator opens allowing the appropriate flow rate of chilled water to pass through the cooling coil. The high temperature air is cooled when it is passed through the heat exchanger of the cooling coil. The cooling coil has the dual role of providing sensible cooling and dehumidification. Sensible cooling is the process whereby the air temperature is cooled down to a lower temperature than the original one. Dehumidification is the process concerned with the amount of vapour or moisture content within the air. The air passing through the heat exchanger is cooled until it reaches its dew point temperature. This is the temperature where the air is not able to carry any more moisture. Condensation occurs and the air is dehumidified at this stage. Often the coil temperature required to dehumidify the air is lower than that required to achieve the required room temperature.

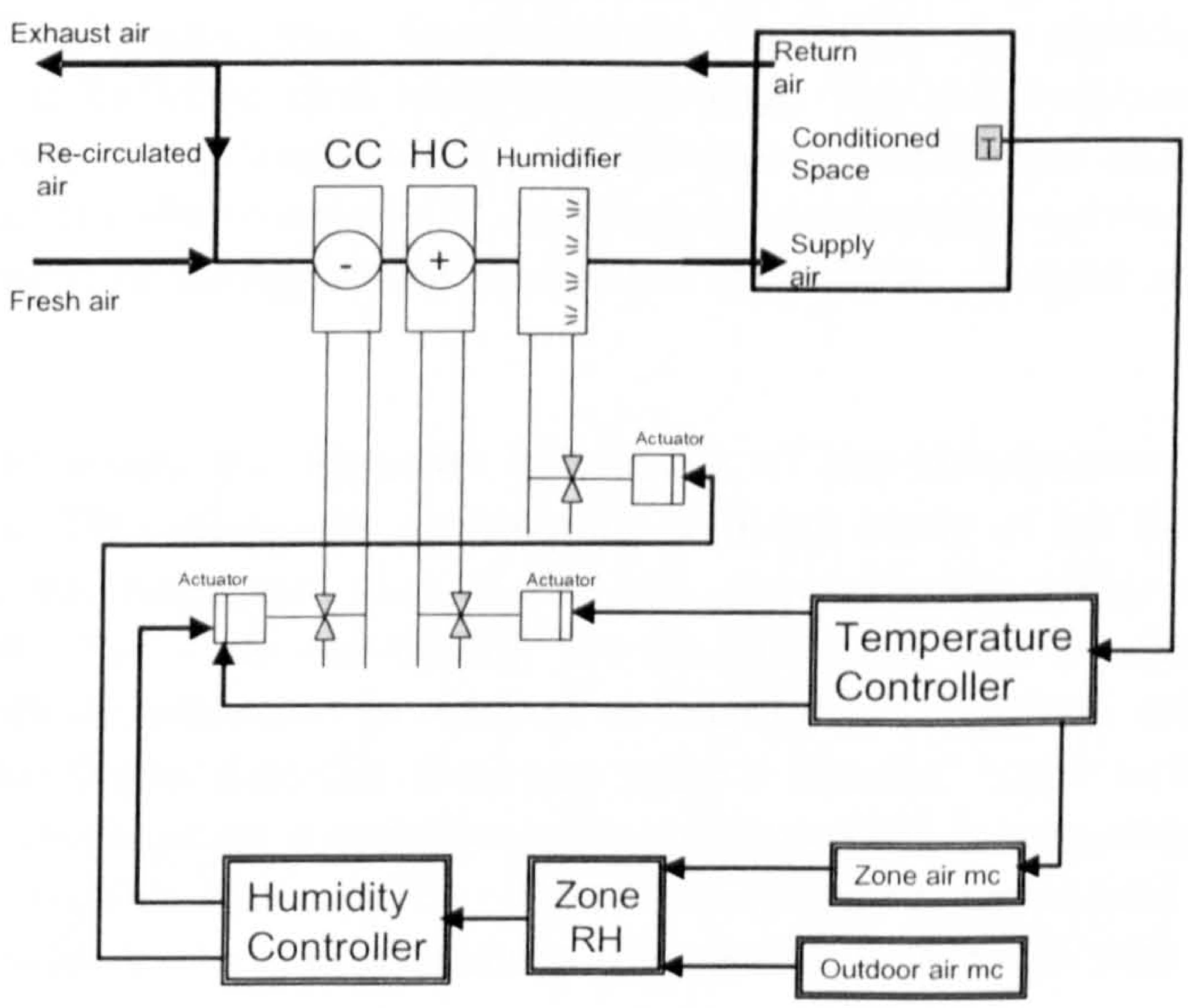

Figure 5.28 Simplified schematic of the building model with the hvac and controllers

Consequently, the dehumidification process often means that the air leaving the cooling coil is at a lower temperature than required for the supply air temperature to the conditioned space. Consequently the air is passed through the heating coil and reheated so that its temperature is raised to the required supply temperature.

The HVAC system model comprises individual models based on the characteristics of all the system components such as cooling and heating coils, actuating valves and dampers and the PID controllers.

5.5 Conclusions

Reducing the energy consumption of buildings requires that the energy problems be known. There cannot be an elegant solution to a misstated problem. More specifically, the reduction of energy use through design is accomplished by

1. Understanding the total energy needs and energy use characteristics of a building, building type, or building function;
2. Understanding the manner in which individual building components interact and contribute to the total energy use;
3. Knowing the various conservation strategies appropriate to the building location, use, and operation, and;
4. Having the ability and tools to calculate the thermodynamics and economics of applying these strategies.

This chapter aimed at examining the effect of zoning on a building cooling demand. A review of buildings and their stereotypes was carried. This provided the base for the development of the stereotypes for modelling, as the main two types of buildings stereotypes most common in Kuwait. As demonstrated earlier in this chapter, the most common forms of modern office buildings found in Kuwait represent either the "deep plan" or "long thin" stereotypes. Consequently, to satisfy the objective of this work, these two forms of building plan have been chosen. The selected two types of layout were used to ascertain the load profiles in relation to orientation and considered how these might affect the development of building environmental services control zoning and the development of strategies for integrated ice storage systems in office buildings in Kuwait.

TAS was used to study the dynamic behaviour of the stereotypical office building models developed. This allowed a preliminary in-depth study of the likely load profiles for typical office buildings, and also, it allowed examining the effect of orientation on the building load. The explored results for the different forms represented showed distinct differences of behaviour in relation to orientation. The load profiles from TAS model showed how the load profile from one zone to another varies with time. The time when a specific zone requires a specific cooling demand other zones located at different orientations may require less cooling. These behaviours suggest and encouraged the introduction of modular ice-storage system that can be associated with zones based on orientation.

The Matlab building model was presented in detail in this chapter. A good correlation was demonstrated when comparing the zonal temperature of both the TAS and the Matlab models. This Matlab model is intended to be the base for the model predictive control (MPC) strategy associated with the ice-storage HVAC model that will be described in greater details in the following chapter.

"With the advent of the communications revolution and microprocessors falling in price and increasing in power, buildings are becoming ever more "intelligent". Combined with a need for low-energy, environmentally-friendly buildings and a requirement to allow occupants a measure of control over their environment, a greater understanding of controls, buildings and their system responses is required" ... Levermore, 2000

Chapter 6

The Ice-storage model with Model Predictive Control

6.1 Introduction

As highlighted earlier in previous chapters, the objective of this research work is to introduce an energy efficient control strategy for air-conditioned office buildings in Kuwait and other countries that fall in the hot arid region. This is through the utilisation of thermal energy storage systems (TES) in the form of ice-storage. Ice-storage systems are known to have the advantage of space saving over chilled water storage systems. However, such systems can be further improved for more optimum use of energy through the application of advanced control methods. To enable the control development aspects of this research work, an ice storage model had to be developed so a modern control strategy can be integrated with such system in order to optimise such systems through the optimum conservation of energy consumed.

Ice-storage systems can have several configurations when working in conjunction with HAVC systems in office buildings. As this was explained in details in the previous chapter, the task in this chapter is to report on the modelling of the ice-storage system type selected for this research work. Examining the model predictive control strategy (MPC) of the chosen configuration that is thought to be most suitable for application in a country like Kuwait will follow the development of the storage modelling.

There are two basic and quite different principles for constructing models (Ljung and Glad, 1994). If the physical laws governing the behaviour of the true system are known these can be used in order to construct a model. This type of model is often referred to as a white-box model. Such a modelling approach has been adopted in the development of the simulink single zone building model. The other principle of constructing a model, which is to be used in the modelling of the chiller and ice-storage model, is based on using measurements of input and output signals from the true system. This way of modelling is known as system identification and the resulting model is called a black-box model.

A series configuration, chiller priority strategy is thought to be most appropriate to be utilised for the case of Kuwait. An indirect, ice-on-coil, system is the type of system chosen to be modelled and studied through the core of this chapter, as it is the most appropriate as has been highlighted in the literature review presented in the previous chapter. As the aim is to incorporate a model predictive control (MPC) strategy to assure optimum operation of the system as whole, the subjects of both system identification and MPC are first introduced.

6.2 System Identification

System identification is a kind of *"reversed engineering"*. This statement certainly needs some justification, Schon (2001). When obtaining a model by using the theory of system identification, the input sequence and the response that the system gives to that particular sequence are used. The system identification theory functions to find the equations which best describe the behaviour of the system given this information. This is why it is referred to as reversed engineering, the answer (the input and output sequences) is already known and the system which produces this answer is what is searched for.

If the problem of identifying a model is analysed it will be found to consist of the following constituents (Ljung, 1999b):

- Experiment design
- Data collection
- Model structure selection
- Model estimation
- Model validation

Experiment design is about designing a proper experiment, which reveals as much information about the system to be modelled as possible. Once the experiments are designed the actual input and output sequences, i.e. the data, have to be collected. When selecting a model structure, the container for the final model is chosen. That is, the number of parameters and how these appear in the model description are determined. The estimation of the model deals with transforming the input and output sequences into the chosen container, by assigning the unknown parameters to appropriate values. The last part of the system identification problem, model validation, deals with finding out how well this transformation modelled the system. That is, it aims at answering the difficult question of whether or not a good model was found.

6.3 Model Predictive Control (MPC)

Model Predictive Control (MPC) refers to a class of algorithms that compute a sequence of manipulated variable adjustments in order to optimise the future behaviour of a plant. In other words, it relies on predictions of the future behaviour of the system to be controlled. These predictions are calculated from a model of this system, thus making the model the cornerstone of the predictive control algorithm, Schon (2001). Originally developed to meet the specialized control needs of power plants and petroleum refineries, MPC technology can now be found in a wide variety of application areas including chemicals, food processing, automotive, aerospace, metallurgy, and pulp and paper, Qin (1996).

The intention is to apply MPC to attempt to operate the HVAC plant at optimum conditions. Predictive Control requires the on-line solution of a constrained optimisation problem. Predictive Control is distinguished from other control methodologies by the following three key ideas, Alswailem (2003):

- An explicit 'internal model' is used to obtain predictions of system behaviour over some future time interval, assuming some trajectory of control variables.

- The control variable trajectory is chosen by optimising some aspect of the system behaviour over this interval.

- Only an initial segment of the optimised control trajectory is implemented; the whole cycle of prediction and optimisation is repeated, typically over an interval of the same length. The necessary computations are performed on-line. These are controls that adapt themselves to changes in their operational domain as well as to changing requirements. They continue to make such adjustments throughout the entire lifetime of the system they are controlling.

They are in fact different from self-tuning controls, which attempt to attain a static optimum in relation to initially unknown, but essentially constant value parameters.

In order to develop such control processes the structures and stages involved should be clearly defined. This process was clearly defined by Watanabe (1997) in terms of figure 5.1.

This structure implies an iterative process through “TRIAL” – “EVALUATION” – “MODIFICATION” in response to training data or, in a longer-term system response with regard to key parameters, to attain required performance criteria.

Adaptive control and MPC is one form of it, can basically be divided into feedforward and feedback systems. These are described in figure 6.2

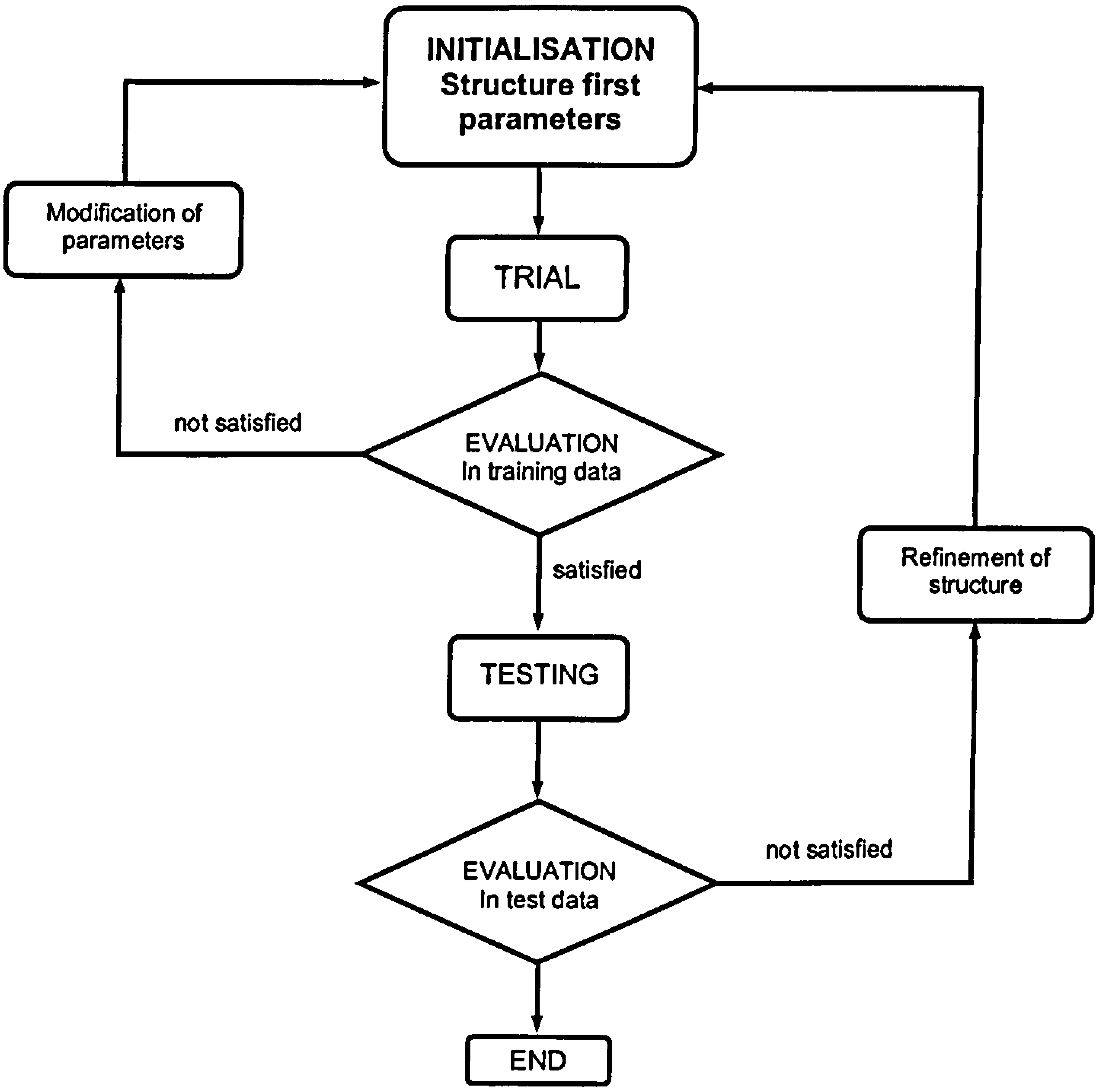

Figure 6.1 Common learning process

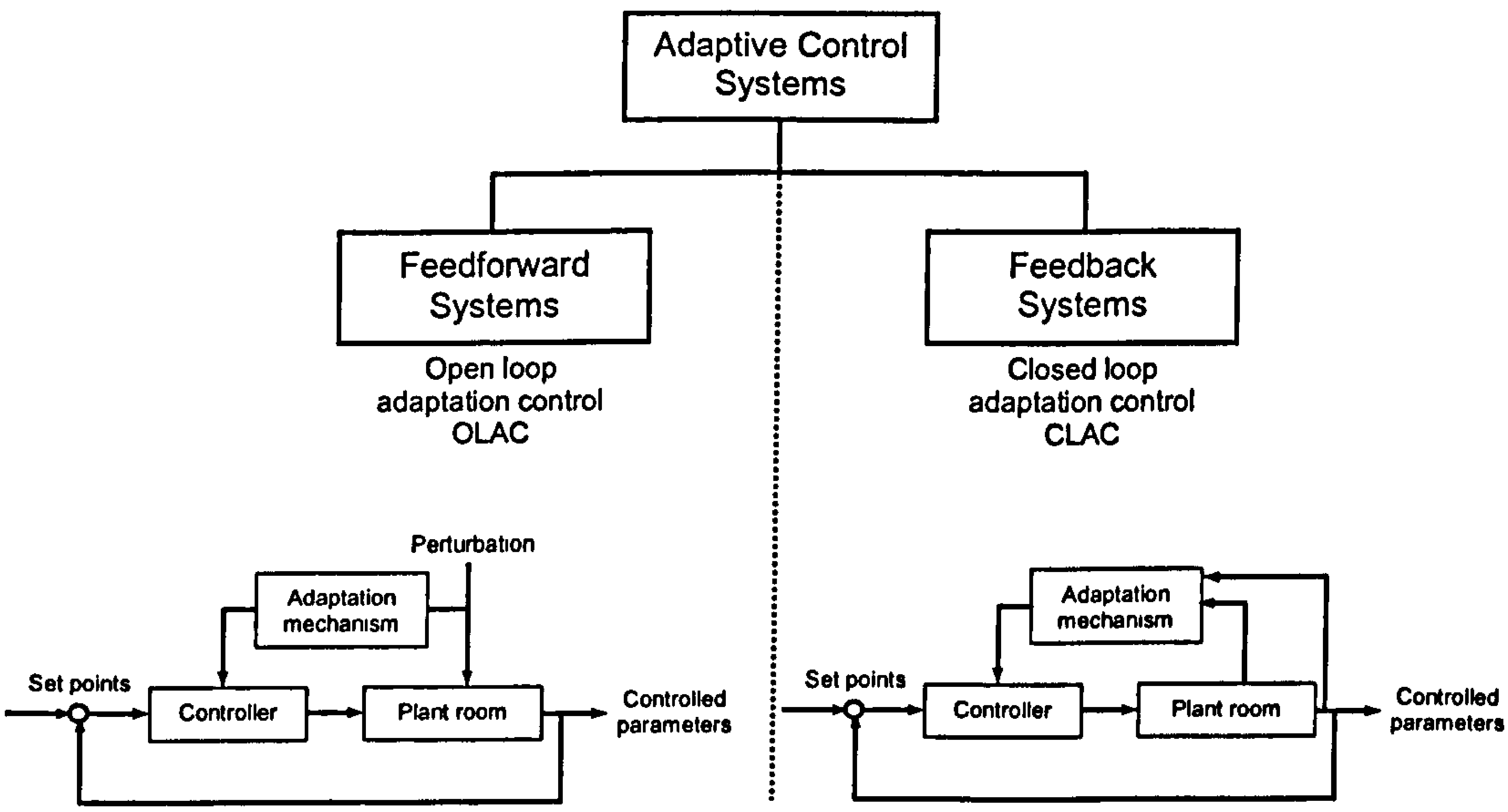

Figure 6.2 Schematics of feedforward and feedback adaptive controls

6.3.1 Feedforward adaptive control systems (OLAC)

In this system perturbations or disturbances of the key controlled parameters are highly correlated with the process parameter variations and are measured and then used to adjust the dynamic controller parameters, usually via a "look-up" table. The controller is adapted as the disturbances occur. In this system Gain scheduling is useful and easy to apply for conditions where plant non-linearity arises from known and measurable inputs. For all of the above issues the application of OLAC can lead to improved performance over conventional controls. A common application is in "compensation" controllers that have system components such as valves that exhibit non-linear behaviours.

One advantage of feedforward controllers is that they react quickly to process change because the process behaviour is known in advance.

6.3.2 Feedback adaptive control systems (CLAC)

Feedback adaptive control systems are most useful in situations where immeasurable system perturbations or changes exist, such as the build up of deposits on heat exchanger surfaces. The actual control performance is measured explicitly or implicitly and then compared with the desired performance. Any variation from the desired performance is used to adjust the control parameters. A great diversity of feedback adaptive controllers exists but these can be classified into two types: Dual adaptive or non-dual adaptive controllers.

6.3.2.1 Dual adaptive controllers

Optimise performance criteria using as much information about the system as is possible through information gathering so that it can generate optimal performance. These controllers require quality information about the system and stochastic properties of the system need to be known in advance. Stochastic properties can be defined as properties that have random probability or distribution patterns that can be analysed statistically but not predicted precisely. This would appear to make dual adaptive controllers impractical, but this condition is often overcome by utilising sub-optimal dual controllers that try to optimise a less ambitious objective.

6.3.2.2 Non-dual adaptive controllers

Minimise design performance criteria by using only present and past values of measured control loop parameters. These systems do not need information about the future. They are again subdivided into two main systems: model reference adaptive control (MRAC) and model identification adaptive control (MIAC).

In the MRAC system a fixed model of the plant under control is applied. This generally takes the form of one (or a set) of differential equations that calculate the desired plant responses from measurements of the current and past status of control parameters. The error between the predicted and actual measurement is used as a basis for adjusting the control parameters. However, this method implies that the system approaches the behaviour of the system reference model, but not necessarily optimal performance.

The MIAC system performs three basic tasks:

(i) information gathering about present process behaviour
(ii) control performance criterion optimisation, and
(iii) adjustment of the controller

These operations are carried out during each measurement interval. This method needs to identify the system for each sample of time to obtain a refreshed model of that system on a regular basis. This can be achieved either by a recursive least squares method or by utilising neural network modelling.

The primary objective of adaptive controllers is to produce a good controller and so the emphasis shifts from control gains, rules and membership functions common to expert systems to defining the objectives of the controller and deciding which measurements best indicate and ensure that these objectives are achieved. Neural network models are compatible with such objectives.

6.4 Approaches towards modelling

To model and properly control a system, an understanding of the logic behind its operation is crucial as a first step towards the development of the system model. Knowledge of the main control variables is essential in order to know what to control and monitor; in order to assure best optimisation of not only the ice-storage system but also the HVAC plant as a whole.

In the case of ice-storage, the system is composed of a tank that is filled with water. The water is in a static state and does not vary in mass or volume when no charging or discharging is taking place. A spiral coil is submerged in the tank. The chilled water that is normally used in a conventional HVAC system is replaced with a coolant liquid that is capable of staying in its liquid phase at temperatures lower than 0 °C. In this case the coolant is a solution is composed of 70% to 75% water and 25% to 30% ethylene glycol solution. The coolant is circulated through the coil during charging "ice making", and discharging "ice melting", processes. For such processes, the system can be considered as a heat exchanger and the modelling of such ice systems in a mechanistic (theoretical) approach requires that heat transfer and heat exchanger design equation be used.

The modelling of the solid-liquid phase change process is a significant part of the design and modelling of an ice storage system. Different modes of heat transfer processes are involved and play an important rule in accurately predicting the thermal performance of the system. In addition, when the thermal performance can be accurately determined, it will overcome the chance of designing and/or selecting an oversized system that will lead to the wasting energy by producing a larger volume of ice than needed. The modelling process of such latent heat type of storage is accompanied by a high level of complexity. The transient heat and mass transfer problems associated with this type of solidification and melting are known as moving boundary problems [Strand (1994) & Jekel (1993)].

Ice-storage systems are related to this sort of class because the process does involve a change in the state of the material contained in the storage tank, which in this case is water. The change of state involved is usually referred to as charging and discharging of the ice storage. The process of ice building by freezing the water is defined as charging. Where as, discharging is the process of melting the ice. Charging takes place during the periods when cooling demand is low, i.e. off-peak. Here, heat will be removed from the water that is stored in the tank causing the change in its phase. When the on-peak time is due the stored energy is utilised.

The strategy and control of the system will depend on whether it is considered as a full storage or partial storage system. As mentioned earlier in chapter 4, if the option is to go for a full storage system, figure 4.10, then the refrigeration plant is used during off-peak to fully charge the storage tank. During on-peak hours, the refrigeration plant is not used at all and the cooling demand is totally met by the ice storage system. In the case of partial storage, whether it is a load levelling or demand limiting strategy, figure 4.11A and 4.11B, the storage is suppose to provide for only a proportion of the demand and the rest will be met by the HVAC system. In the case of this research work the option is to go for a partial storage with a load levelling control strategy.

While the demand for thermal energy storage has grown steadily during the past decade, work on the analysis and modelling of the phase change process of these systems has been limited. The majority of those resources concentrate on the melting and solidification analysis in spherical geometry and only very little work has been done on analysing storage systems with cylindrical geometries.

An ice storage system can be modelled based on heat exchanger analysis. Heat exchangers transfer heat from one fluid to another. The fluids are not in direct contact and are separated by a solid surface as they pass through the heat exchanger. Heat transfer occurs between the fluids because of the temperature difference that exists between them. Heat transfer can be either in the form of sensible heat or latent heat. If the heat transfer process occurs directly between the two fluids, which remain in a particular state, then it is defined as sensible heat transfer. On the other hand, when the heat transfer process involves the change in the phase of one of the fluids, then it is defined as latent heat transfer. In the case of ice-storage systems, the process of charging and discharging takes the sequence of sensible heat when cooling down the water at the beginning of the freezing process and then latent heat at the stage when water is changing from its liquid state into ice, its solid state. Finally, sensible heat when the temperature of the ice in the tank is going below 0 °C.

For the heat exchanged between two fluids flowing through a heat exchanger, the rate of heat transferred can be calculated using

$$Q = UA\,\Delta t_m \qquad \textbf{Equation 6.1}$$

where

U = overall heat transfer coefficient from fluid to fluid
A = heat transfer area of the heat exchanger associated with U
Δt_m = Log mean temperature difference (LMTD)

For a heat exchanger with a constant U, Δt_m is calculated as

$$\Delta t_m = C_f \frac{(T1-t2)-(T2-t1)}{\ln(T1-t2)/(T2-t1)}$$ **Equation 6.2**

The temperature distribution is shown in figure 6.3 below.

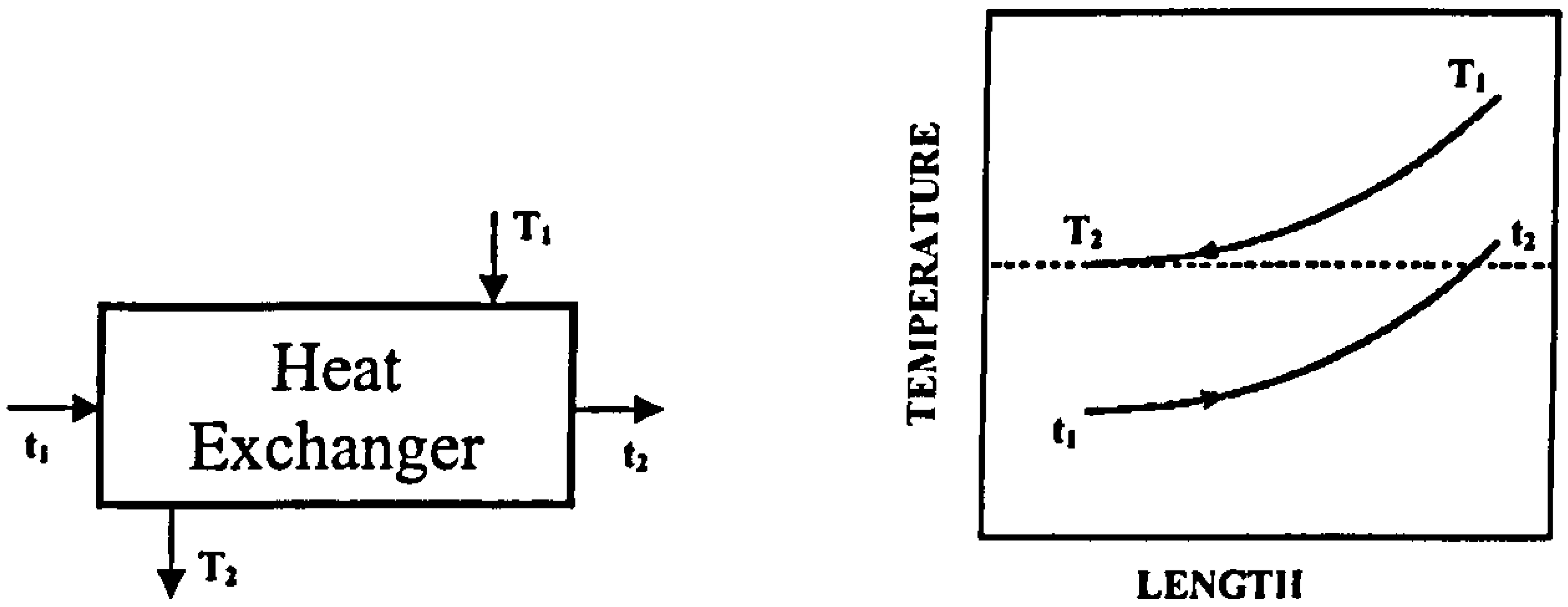

Figure 6.3 Temperature distributions in a counter flow heat exchanger

If the heat exchanger is assumed to be acting as a counter flow heat exchanger then the correction factor, C_f, is assumed to be 1. The load for each fluid can be calculated from energy balance on each fluid

$$Q = m\, c_p (t_{in} - t_{out})$$ **Equation 6.3**

The value of Δt_m is an important factor in heat exchanger selection. If the value of Δt_m is high, a relatively small heat exchange surface area is required for a given load. When the **approach temperature** (The difference between T_2 and t_1) is small, Δt_m is also small and a relatively large heat transfer area A is required.

It is assumed that the intended ice storage tank will be acting effectively as a counter flow heat exchanger. The two fluids involved in the heat exchange process are the coolant solution from the chiller, which cools the store, and the water (ice) being stored. In this case, water is not flowing through the heat exchanger and thus does not have a flow rate associated with it. Instead, the water is undergoing a phase change and is assumed to remain at a constant temperature. This means that the temperature remains constant at the freezing point of water. When the charged tank is discharged, the stored ice is considered to be the cold fluid. In this case, $T_{cold,in} = T_{cold,out} = 0$ °C. When the storage unit is being charged, the "hot" fluid remains at 0 °C. Hence, the equation for heat transfer rate is represented by the energy balance equations below

$$q = \dot{m}_{hot}\, c_{p,hot} (T_{hot,in} - T_{hot,out})$$ **Equation 6.4**

$$q = \dot{m}_{cold}\, c_{p,cold}\,(T_{cold,out} - T_{cold,in})$$ **Equation 6.5**

$$q = \rho(\Delta V_{ice})h_{fusion}$$ **Equation 6.6**

where

ρ = density of ice, (kg/m^3)
ΔV_{ice} = change in volume of ice stored, (m^3)
h_{fusion} = latent heat of fusion of water, (W/kg)

To relate this to the LMTD method of analysing heat exchangers, the temperatures in figure 6.2 are defined with relation to the temperatures of the coolant and the ice in the tank:

$$\Delta T_{lm} = \frac{(T_{brine,in} - T_{freeze}) - (T_{brine,out} - T_{freeze})}{\ln[(T_{brine,in} - T_{freeze})/(T_{brine,out} - T_{freeze})]}$$ **Equation 6.7**

and so:

$$q = UA\Delta T_{lm}$$ **Equation 6.8**

Strand (1994), derived a specific relation between the product of the overall heat transfer coefficient and the total heat exchanger surface area, UA, for an internal melt ice-on-coil system. For charging, the following relationship for UA can be expressed by noting the cylindrical nature of the heat exchanger tubing in the ice-on-coil system:

$$UA = \frac{1}{\left\{\frac{1}{2\pi h r_{id} L} + \frac{1}{2\pi k_{tw} L}\ln\left[\frac{r_{od}}{r_{id}}\right] + \frac{1}{2\pi k_{ice} L}\ln\left[\frac{r_{int}}{r_{od}}\right]\right\}}$$ **Equation 6.9**

where

L = total length of the tubing, (m)
K_{tw} = thermal conductivity of the tube walls, (W/m.°C)

In the discharge cycle, the equation takes on a similar form with one added complication. The conduction between the outside surface of the heat exchanger tubing and the solid-liquid interface is replaced by a natural convection term. The equation for discharging is

$$UA = \frac{1}{\left\{\frac{1}{2\pi h r_{id} L} + \frac{1}{2\pi k_{tw} L}\ln\left[\frac{r_{od}}{r_{id}}\right] + \frac{1}{2\pi k_{eff} L}\ln\left[\frac{r_{int}}{r_{od}}\right]\right\}}$$ **Equation 6.10**

where

k_{eff} accounts for natural convection and can be expressed for the space between concentric cylinders as

$$k_{eff} = 0.386 k_{water}\left(\frac{\Pr}{0.861+\Pr} Ra_c^{*}\right)^{0.25}$$ **Equation 6.11**

where

Pr = Prandtl number of water at some average temperature;

$$Ra_c^{*} = \frac{\left(\ln\left(\frac{r_{int}}{r_{od}}\right)\right)^4}{\lambda^3\left[(2r_{int})^{-3/5} + (2r_{od})^{-3/5}\right]^5} Ra_\lambda;$$

$\lambda = r_{int} - r_{od}$;

$$Ra_\lambda = \frac{g\beta(T_{od} - T_{freeze})\lambda^3}{\nu\alpha};$$

g = gravitational constant, (m^2/s);
β = volumetric thermal expansion coefficient, ($^oC^{-1}$);
T_{od} = temperature at the outer surface of the tubing, (^oC);
ν = kinematic viscosity, (m^2/s)
α = thermal diffusivity, (m^2/s)

The above equation is valid for $10^2 \leq Ra_c^{*} \leq 10^7$.

The use of heat exchanger analysis for the indirect ice storage system adopted provides the basis of the approach being taken regarding the development of the of the ice storage component of the system model. The key to the success of this analysis is to be able to define the parameter UA, which will change with the geometry of the system, as described by equation 6.9 and equation 6.10. The key variables that will vary with geometry are the convection coefficient for heat transfer and the interface radius, r_{int}, between the solid ice and the water. In many cases it is even possible to consider that the convective heat transfer coefficient will remain essentially constant.

Utilising these assumptions and applying them to equation 6.10 allows it to be expressed in the form:

$$UA = \left[G_1 + G_2\left(\frac{1}{r_{\text{int}}}\right)\right]^{-1}$$ **Equation 6.12**

It can be shown that the interface radius has a relationship with the fraction to which the system is charged, P_c, in relation to the fully charged ice radius, and so

$$UA = \left[G_1 + G_3 f(P_c)\right]^{-1}$$ **Equation 6.13**

Based on a mechanistic analysis of the melting and freezing of water around the coils, Jekel (1993), presents the heat transfer process during the charging and discharging periods. The charging process is split into three periods: sensible charging, unconstrained latent charging, and constrained latent charging. With a tank that is completely filled with water and assuming an initial state of a unified initial temperature, and no ice formation taking place in this period, the energy balance equation is

$$\dot{Q}_b + \dot{Q}_{gain} = m_w c_w \frac{dT_w}{dt}$$ **Equation 6.14**

The sensible energy heat transfer process ends when the average water temperature in the tank becomes zero. At this condition the unconstrained latent charging starts and ice formation is initiated on the coil surface. Because the ice diameters on the adjacent coils do not intersect, the name unconstrained latent charging is given to this process. Neglecting the sensible term allows the energy balance to be written as

$$\dot{Q}_b + \dot{Q}_{gain} = -h_{if} \frac{dm_{ice}}{dt}$$ **Equation 6.15**

Jekel states, the constrained latent charging starts when the ice cylinders formed during the freezing process touch. During this period, the heat transfer is no longer one-dimensional and the boundary conditions preclude an analytical solution. Jekel, refers to a numerical analysis to determine the thermal resistance for specific geometries. In addition he uses a finite element heat transfer program, FEHT, to numerically determine the thermal conductance for a range of ratios of tube diameter to tube spacing. Then from the results, a correction factor is developed to correct the analytical expression for one-dimensional heat transfer through the ice cylinder when the ice cylinders just touch.

The analysis for the discharge period will be split into two periods. First, is the unconstrained latent discharging; and second is the constrained and sensible discharging. The unconstrained latent discharging period is characterised by a cylindrical melting of ice around the outside of the tubes. The sensible internal energy change in the ice is small since the ice is assumed to melt at constant temperature. However, the sensible internal energy change in the water can be significant.

$$\dot{Q}_b + \dot{Q}_{gain} = -h_{if}\frac{dm_{ice}}{dt} + m_w c_w \frac{dT_w}{dt} \qquad \textbf{Equation 6.16}$$

After the water formations intersect, the heat transfer occurs from the coolant to the water and then from the water to the ice. Heat transfer coefficients between the tube and the water and between the water and the ice for this geometry are not known, Jekel states. It is assumed that the overall conductance-area product between the tube and the water when the water formations intersect remains constant during the rest of the discharging period.

6.5 Modelling Methodology

The purpose of introducing the two examples above is to illustrate the complexity of the process of modelling ice-storage systems. Very detailed design and geometrical data would be required from manufacturers who may not wish to supply such details.

This high level of complexity suggests the need for a much simpler modelling strategy for such systems. In practical applications, a modelling approach that does not involve the need for detailed design data generally is most suitable. Such an approach towards the modelling of a system without the need for using detailed design information and data and concentrating only on the modelling of the system behaviour as a whole is known sometimes as black box modelling.

The discussion and representation of detailed design methodology of ice storage systems was not the main objective of this research work, which is focused on the development of a model predictive control (MPC) strategy that is able to optimise the energy performance of integrated ice thermal energy storage HVAC system to be used in office buildings in Kuwait. The function of the MPC is to search for the best operating conditions of the system as whole and to optimise the operation of the system. Consequently, simple but robust representative models of both the chiller and ice storage unit were developed for use in conjunction with the Building and *Air Handling Unit* (AHU) simulink models.

The chiller model has been represented by an air cooled YORK chiller. Cooling capacities data for a chiller that has the capability of operating at low temperatures is utilised with ethylene glycol as the secondary coolant, instead of water that is normally used in conventional air-conditioning systems. Different cooling capacities of the chosen chiller at a range of coolant temperatures and ambient temperatures were used. Coolant temperatures representing the chiller outlet temperature T_{cho} ranged between -8 °C to 8 °C. Ambient temperatures were considered to range between 30 °C and 50 °C.

The relevant chiller performance data was re-created in a Matlab library so that the system can access the data simultaneously at the time the modelled system is running.

The charging and discharging performance profiles for a Calmac, model 1320, ice storage unit, Calmac Manufacturing Corporation, (Calmac), were used to develop the model of the ice storage unit. This obviated the need for access to detailed design and geometrical data for manufactured systems. The charging and discharging model profiles were digitised and converted into look up data tables that represented the ice storage reference library. The software package called *"ENGUAGE"*, (ENGUAGE), was used for performing this part of the work by digitising the graphs and developing mathematical algorithms of the performance lines. The digitised look up tables derived from these data are presented in Appendix B. Figure 6.4 and Figure 6.5 represent a sample of the manufacturer's data used.

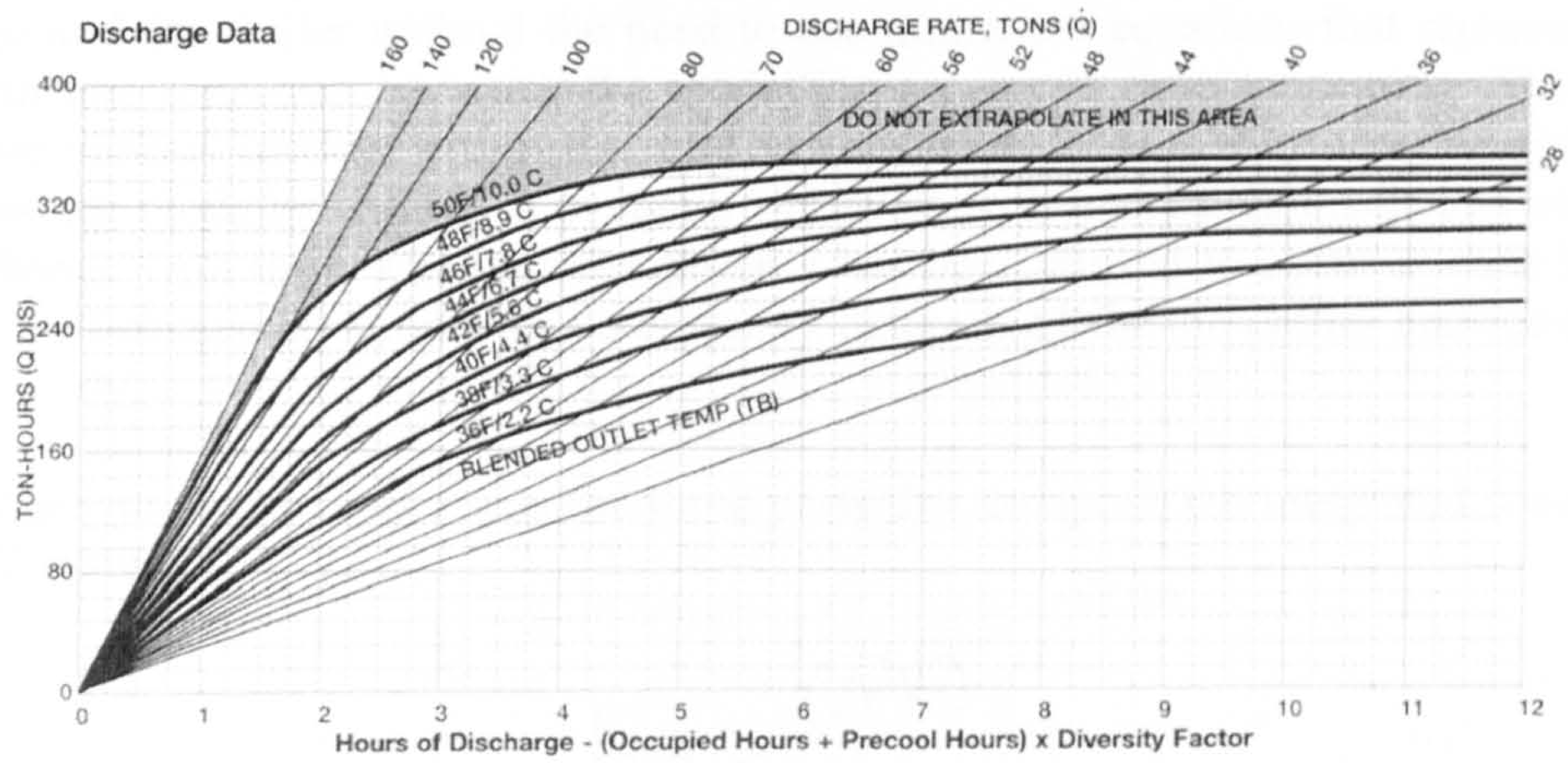

Figure 6.4 Ice-storage discharge sample graph for Calmac model 1320

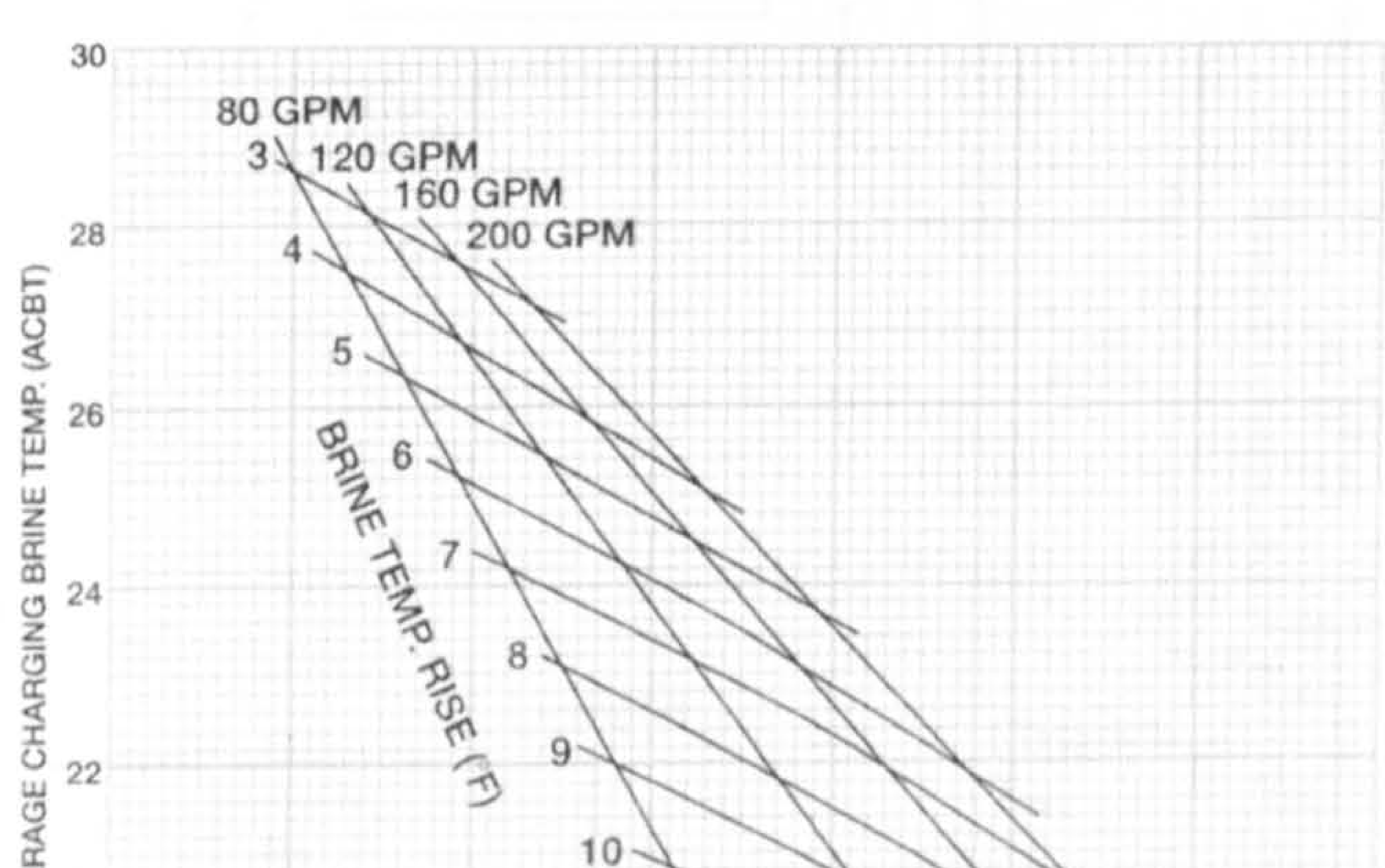

Figure 6.5 Ice-storage charge sample graph for Calmac model 1320

To incorporate an ice-storage system into a simulation process, knowledge of what information is available and what information must be determined is essential. The simulation of the systems comprises three parts. First, the building structure is analysed to determine the heating and cooling loads based on weather conditions, internal loads, and the occupancy schedule of zones within the building. Then, the air-handling system is simulated to provide a system performance to meet the necessary heating and cooling loads. Finally, the central plants, including the ice storage system, are simulated to determine the duty of each component, chiller and ice-storage, to supply the demand of the building. The achievement of models for the first two requirements has been covered in the previous chapters.

Once models of both the building structure and the air-handling system were developed, then much of the information needed to simulate the ice-storage unit was already obtainable. Although the aim was to develop a model that represented both the ice storage and the chiller without the need to use numerical equations that represent each of them one consequence is that the modelling process is time consuming. This arises because various models within the total system have to deal with non-linearities and because the modelled system is dynamic and deals with many parameters and variables that change with time. The iteration process has been chosen to occur at each hour to allow well-chosen conditions to be correctly determined for the chiller and ice-storage respectively.

The schematic below represents the three parts that compose the integrated ice-storage HVAC system.

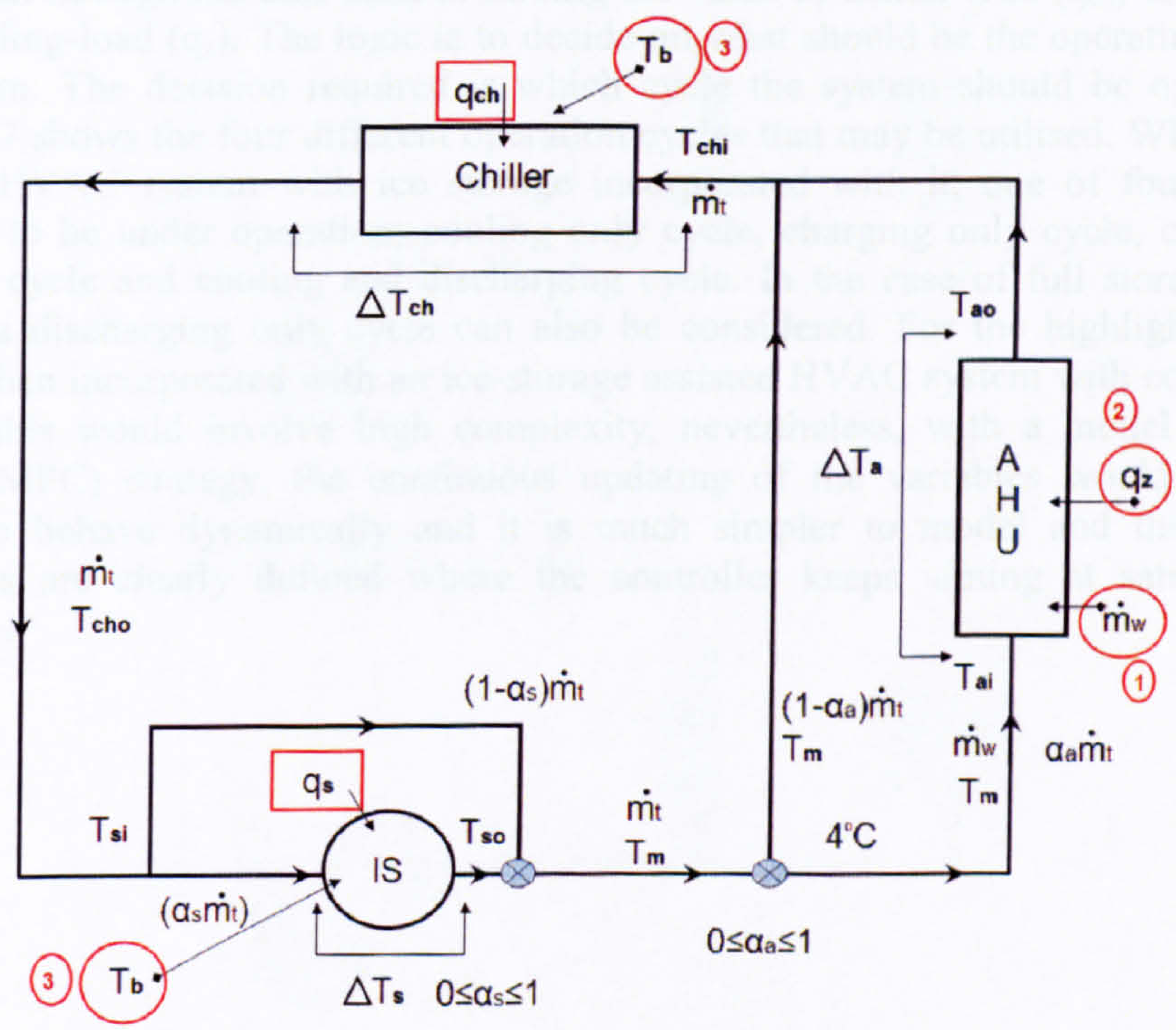

Figure 6.6 Layout of the HVAC plant with ice-storage

The MPC algorithm introduced in this research work attempts to optimise the dynamic behaviour of the ice storage system through the optimisation of the HVAC plant as a whole represented in the chiller and AHU components. This is to be achieved by allowing the adjustment of the dynamically manipulated variables to optimise the future behaviour of the system. The model simulation is to be provided with some initial conditions that are specified at the start of the simulation process. Initial simulation runs with simulink are then conducted. Different mixing temperatures (T_m) that allow variation in the values of other operating conditions that are used as input parameters within the chiller and ice storage parts of the model are generated. Operating conditions such as the zone cooling-load (q_z), the ***A****ir* ***H****andling* ***U****nit* (AHU) outlet temperature (T_{ao}), AHU cooling valve opening are then generated. This is to be carried out for every hour for any chosen period, a one-day, 24-hour period a shorter duration or for a longer duration than one-day day. Mixing temperature (T_m) is assumed to be equal to the cooling coil inlet temperature (T_{ai}) going into the AHU in the first step only. In addition, a preliminary value for the mixing temperature (T_m) is first assumed as an initial guess to start the iteration process with.

The model uses input variables and different operating conditions derived from the previous day, or even the current day, operation to simulate the system and predict the optimum operating conditions. In the case of the simulated system, after the zone cooling load (q_z) has been determined and the ambient temperature (T_{amb}) for the current hour is identified, then the model will search through the chiller library for optimum chiller operating capacity (q_{ch}) that would best serve to meet its duty.

The search through the data aims at finding the value of chiller load (q_{ch}) closest to the zone cooling-load (q_z). The logic is to decide on what should be the operating mode of the system. The decision required is which cycle the system should be operated on. Figure 6.7 shows the four different operation cycles that may be utilised. When dealing with an HVAC system with ice storage incorporated with it, one of four cycles is expected to be under operation; cooling only cycle, charging only cycle, cooling and charging cycle and cooling and discharging cycle. In the case of full storage control strategy a discharging only cycle can also be considered. For the highlighted cycles above, when incorporated with an ice-storage assisted HVAC system with conventional control, this would involve high complexity, nevertheless, with a model predictive control (MPC) strategy, the continuous updating of the variables would allow the system to behave dynamically and it is much simpler to model and the optimum conditions are clearly defined where the controller keeps aiming at satisfying the conditions.

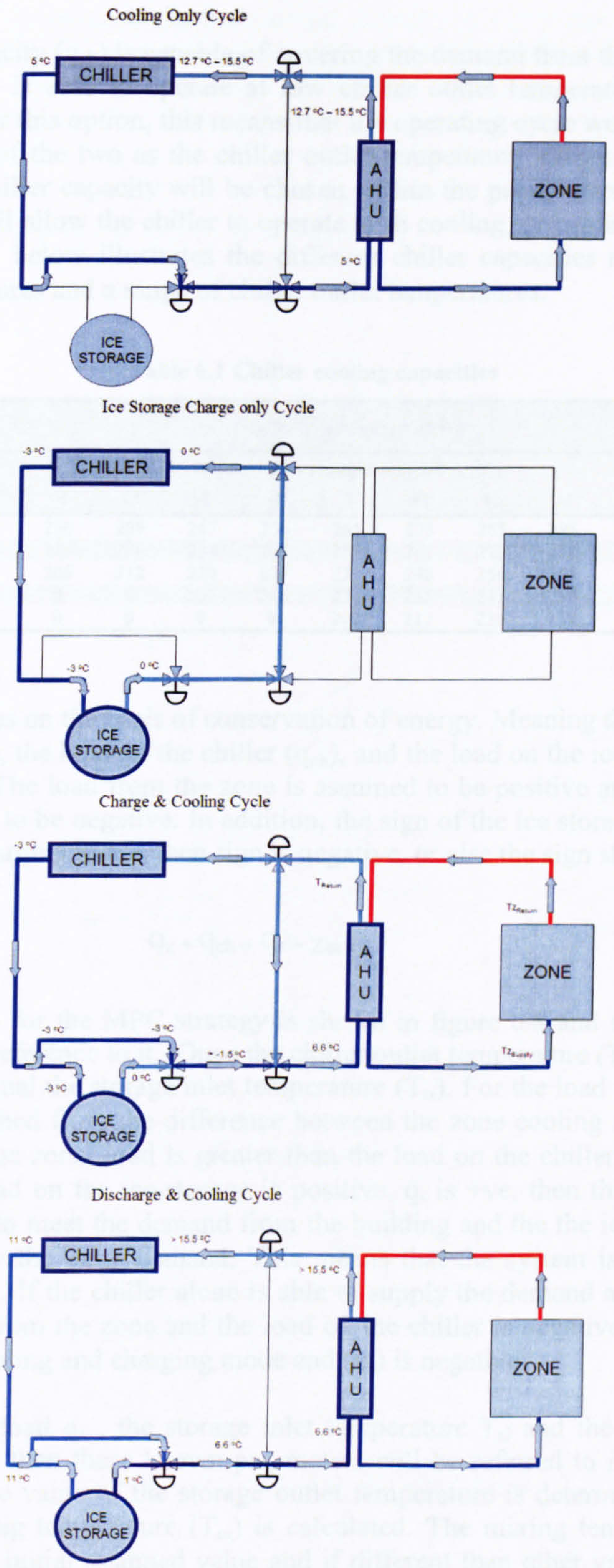

Figure 6.7 The different cycles of HVAC systems with ice storage with conventional control

If the chiller capacity (q_{ch}) is capable of covering the demand from the zone (q_z) and the selected capacity is able to operate at low chiller outlet temperature (T_{cho}) then the choice is to go for this option, this means that the operating cycle would be cooling and charging or any of the two as the chiller outlet temperature allows for either options. Otherwise, the chiller capacity will be chosen within the positive temperature range of (T_{cho}) and this will allow the chiller to operate with cooling, or cooling and discharging cycles. Table 2.1 below illustrates the different chiller capacities related to different ambient temperatures and a range of chiller outlet temperatures.

Table 6.1 Chiller cooling capacities

T_{amb} (°C)	Chiller power output (kW)																
	Chiller output temperature, T_{cho} (°C)																
	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8
30	195	203	212	221	230	239	247	256	265	275	285	295	305	306	307	308	309
35	183	191	200	208	217	226	234	243	252	261	270	280	290	291	292	293	294
40	0	0	0	0	205	212	220	228	239	248	256	265	275	276	277	278	279
45	0	0	0	0	0	0	207	215	224	233	241	250	260	261	262	263	264
50	0	0	0	0	0	0	0	0	209	217	226	235	245	246	247	248	249

The model operates on the basis of conservation of energy. Meaning the sum of the load from the zone (q_z), the load on the chiller (q_{ch}), and the load on the ice storage (q_s), will be equal to zero. The load from the zone is assumed to be positive and the load on the chiller is assumed to be negative. In addition, the sign of the ice storage will depend on whether it is in charging mode, then sign is negative, or else the sign should be positive.

$$q_z + q_{ch} + q_s = \mathbf{Zero} \qquad \textbf{Equation 6.17}$$

The logic diagram for the MPC strategy is shown in figure 6.8 and the following text should be read in reference to it. Once the chiller outlet temperature (T_{cho}) is found then it is assumed to equal the storage inlet temperature (T_{si}). For the load related to the ice-storage, is established from the difference between the zone cooling load and the load on the chiller. If the zonal load is greater than the load on the chiller, ($q_z > q_{ch}$), then this means that load on the ice-storage is positive, q_s is +ve, then this means that the chiller is not able to meet the demand from the building and the the ice-store would be expected to supply the extra demand. This means that the system is in "cooling and discharging mode". If the chiller alone is able to supply the demand and the difference between the load from the zone and the load on the chiller is negative, this means that the system is in cooling and charging mode and (q_s) is negative.

When the storage load q_s , the storage inlet temperature T_{si} and the flow rate in the system are known, then these known parameters will be referred to in the ice-storage data library and the value of the storage outlet temperature is determined (T_{so}). From this step, the mixing temperature (T_m) is calculated. The mixing temperature (T_m) is compared with the initial assumed value and if different then other values needs to be re-adjusted up on the new value of the mixing temperature (T_m). Consequently, the cycle is repeated again until converging to the appropriate values for the current simulation hour. The sum of the three loads, Equation 6.17, is the converging criteria. When the sum of the three loads is equal to zero with an allowable error of +/- 5% then the iteration has experienced convergence. Then the same process is repeated for the total period specified, whether the required period is just few hours one day or longer.

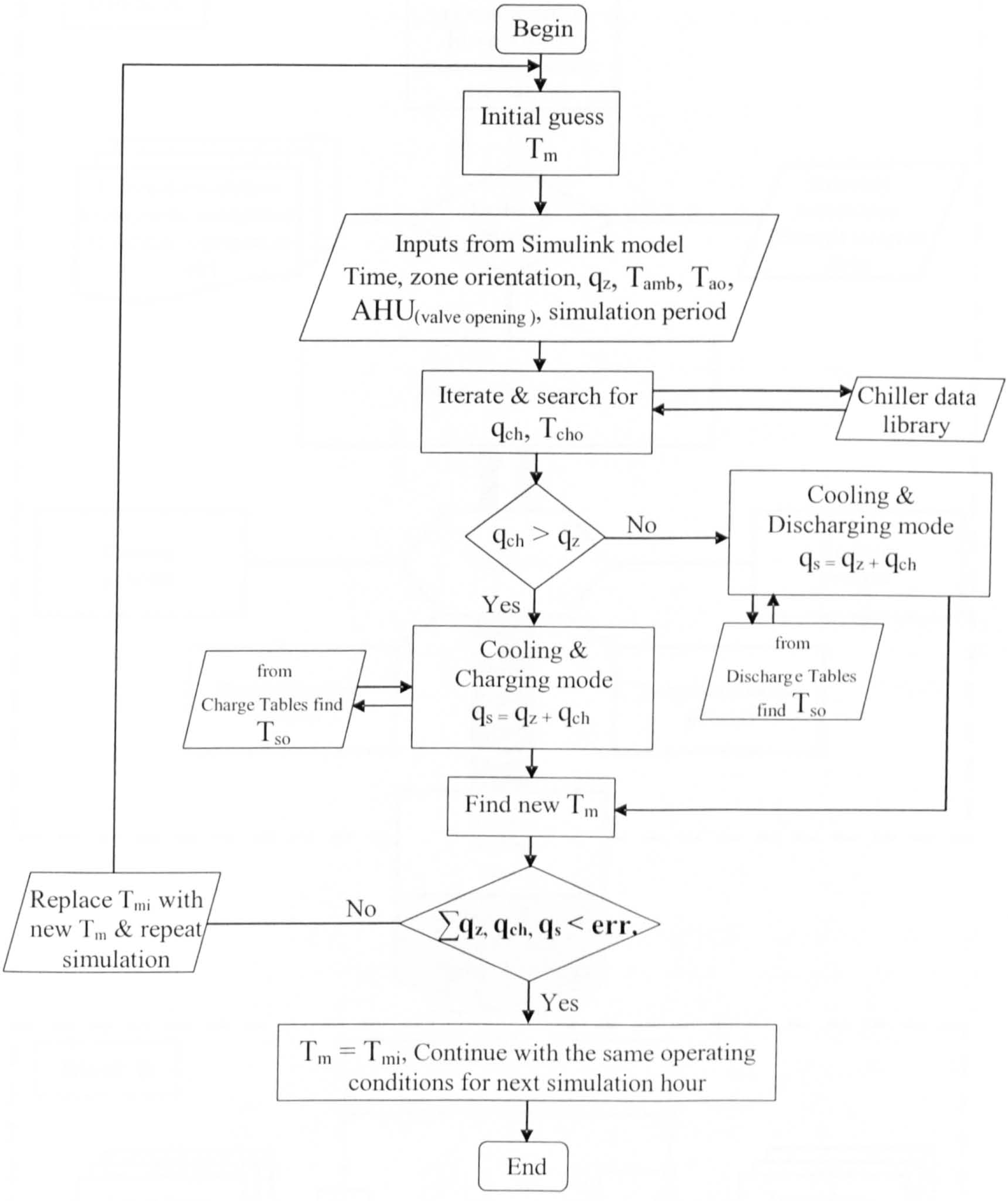

Figure 6.8 Logic diagram for the MPC strategy

In order to introduce the complete picture in a clear framework, the Simulink building model with the air handling unit (AHU), explained in detail in the previous chapter, and the HVAC plant with the ice-storage, explained in detail in this chapter, are introduced in the figure below to help demonstrate how the modelled systems link together.

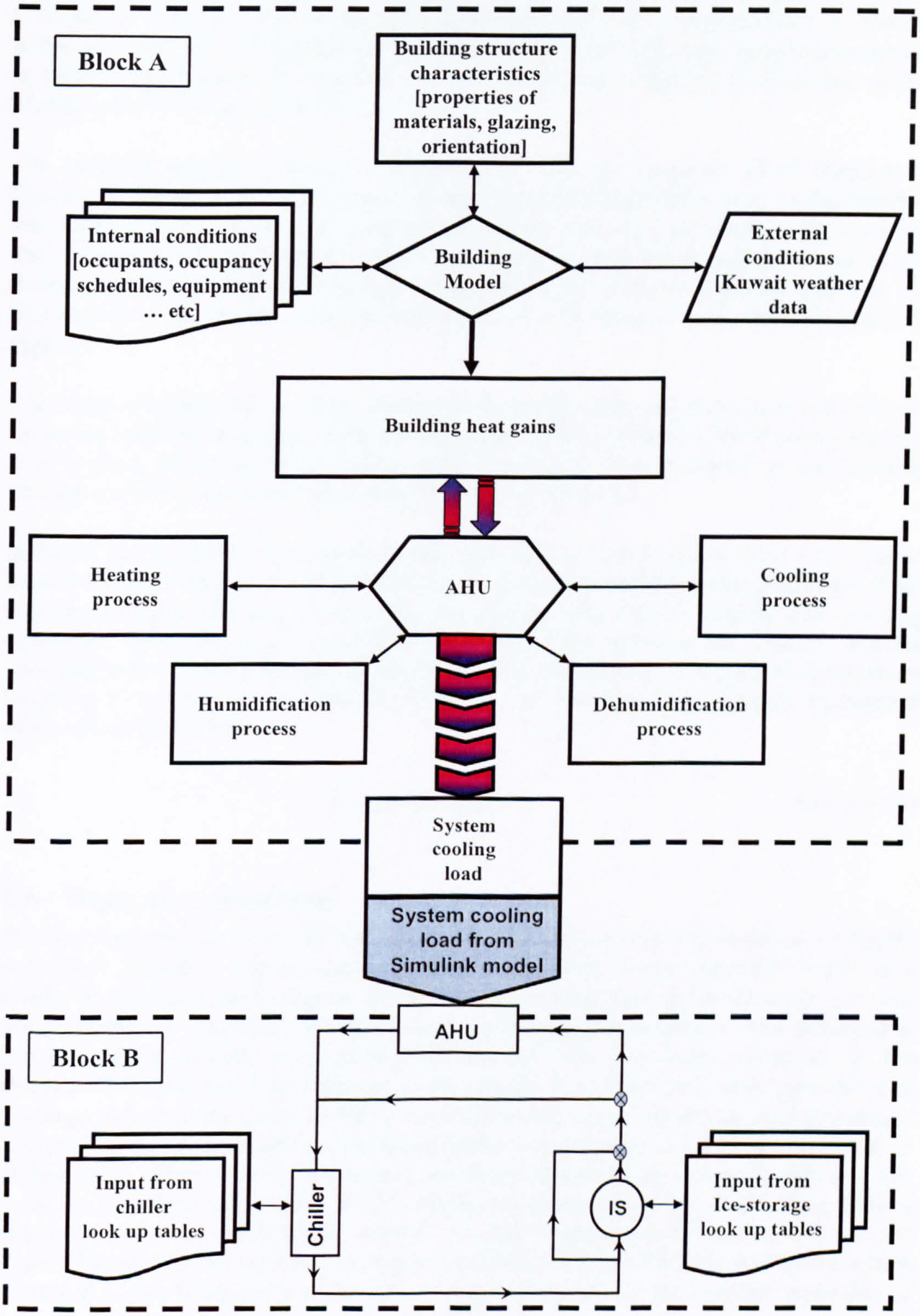

Figure 6.9 Flow diagram describing how the modelled systems link together
Block B corresponds to Figure 6.8, Block A corresponds to Figure C.1 in Appendix C

Figure 6.9 represent the modelling process in two major blocks. Block A describes the building and air handling unit Simulink models that were explained in detail in Chapter 5. Block B describes the chiller and ice-storage with MPC, programmed in Matlab, within this chapter. A schematic of the system in Block B with more details is presented in Figure 6.6. Figure 6.8 describes the logic and how it applies to operation of the Matlab code found in Appendix C.

The building model in Block A is illustrated with the Simulink block diagram in Chapter 5, Figure 5.16. Its function is to examine the thermal behaviour of the building with respect to the effect of the weather parameters, such as solar radiation for example, and internal building conditions, such as occupancy scheduling and the effect of the structure of the building itself present in the form of the different building materials. An illustration of the external and internal gains of a building is provided in Chapter 5, Figure 5.15.

The output of the building model relating to the building thermal behaviour is accounted for as the building heat gain. When cooling needs to be provided to the building the heat gain is then converted to a cooling load. Cooling is then provided to the building through the AHU, the lower section of Block A in Figure 6.9.

In Block B, the chiller is required to deal with the cooling load, provided as an output from the models in Block A. The MPC (controller) is required to make decisions. If the building cooling load (q_z) ≤ (q_{ch}) then the system shall run on cooling and charging operation. When the (q_z) > (q_{ch}) then the chiller must work on full capacity and the shortage in the cooling demand is supplied by the ice-storage. The modelled system is targeting to achieve the satisfaction of the law of conservation of energy highlighted earlier and listed below

$$q_z + q_{ch} + q_s = Zero \qquad \text{Equation 6.18}$$

6.6 Notes on Computing

All three systems, the simulink building model, the chiller and the ice-storage are highly non-linear systems. The interaction between the three would naturally result in a similarly non-linear performance. A number of problems had to be solved to get over this problem. For example, the chiller and ice-storage performances were modelled at the start using smooth polynomial functions to deal with finer variations in the characteristics and smoother response in the system. Very often, this strategy resulted in the large swings in predicted performance and the polynomial model stopped operating. The profiles of the produced polynomials from the manufacturer's data are presented in Figure 6.10. When running the model, we faced the problem of non-linearity as the main three system components (AHU, chiller and ice-storage) start interacting. This is where the point of conflict was created. As each component was trying to meet the required conditions through processing the polynomials describing the performance data it created higher complexity to the system rather than making the problem amenable to solution. Consequently, the decision was made to make use of look up tables derived for the chiller (Table 2.1) and ice-storage system, Appendices A and B.

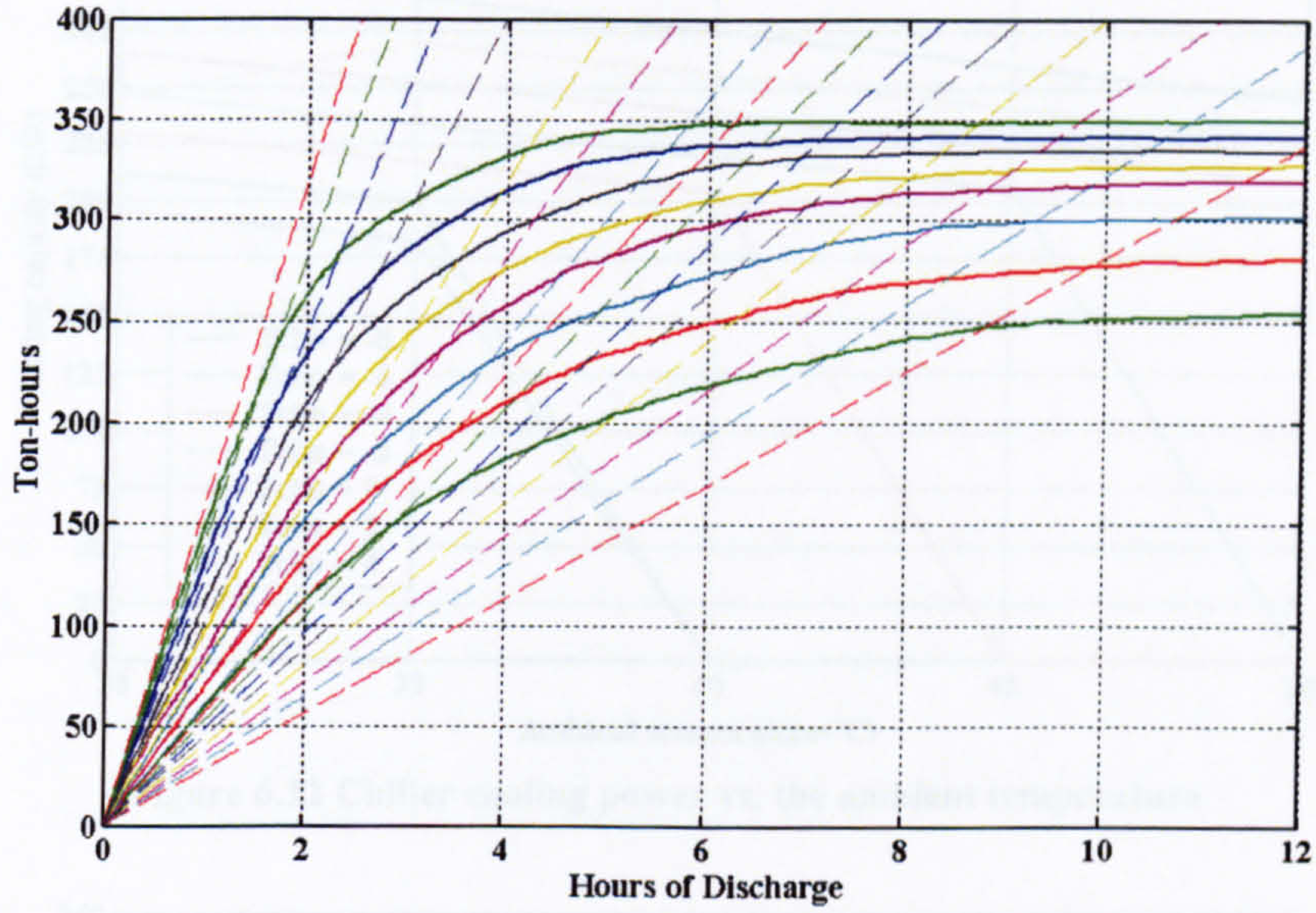

Figure 6.10 Ice-storage discharge sample graph for Calmac model 1320

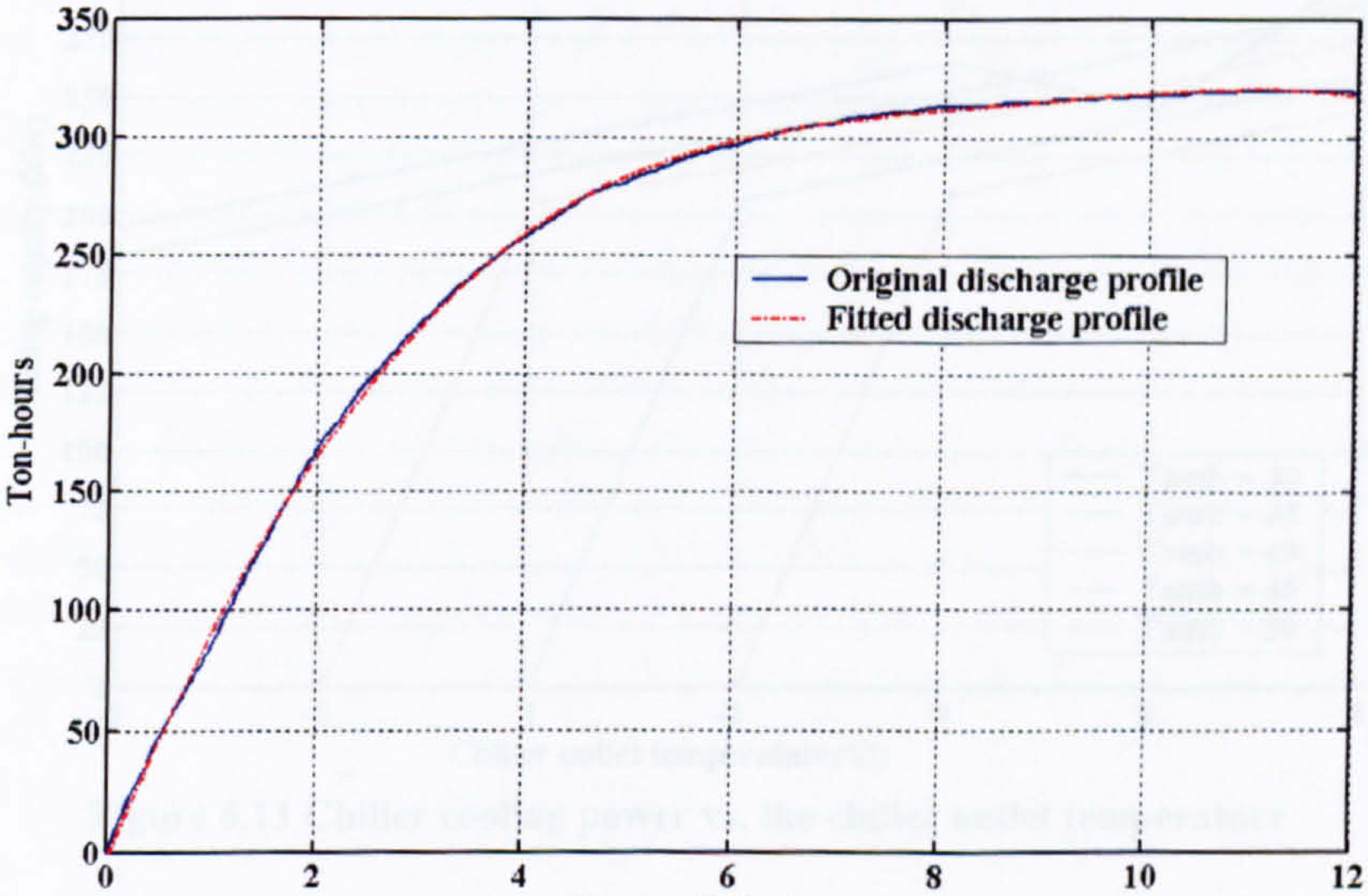

Figure 6.11 Graph showing comparison between plots of fitted and catalogue values [storage discharge]

The figures above and the two chiller performance figures below demonstrate how each component behaves. Initially it was assumed that fitting polynomials to this data would make the provision of input data simpler and more accurate, yet, it was discovered that in fact it made it more complicated by causing the models to oscillate.

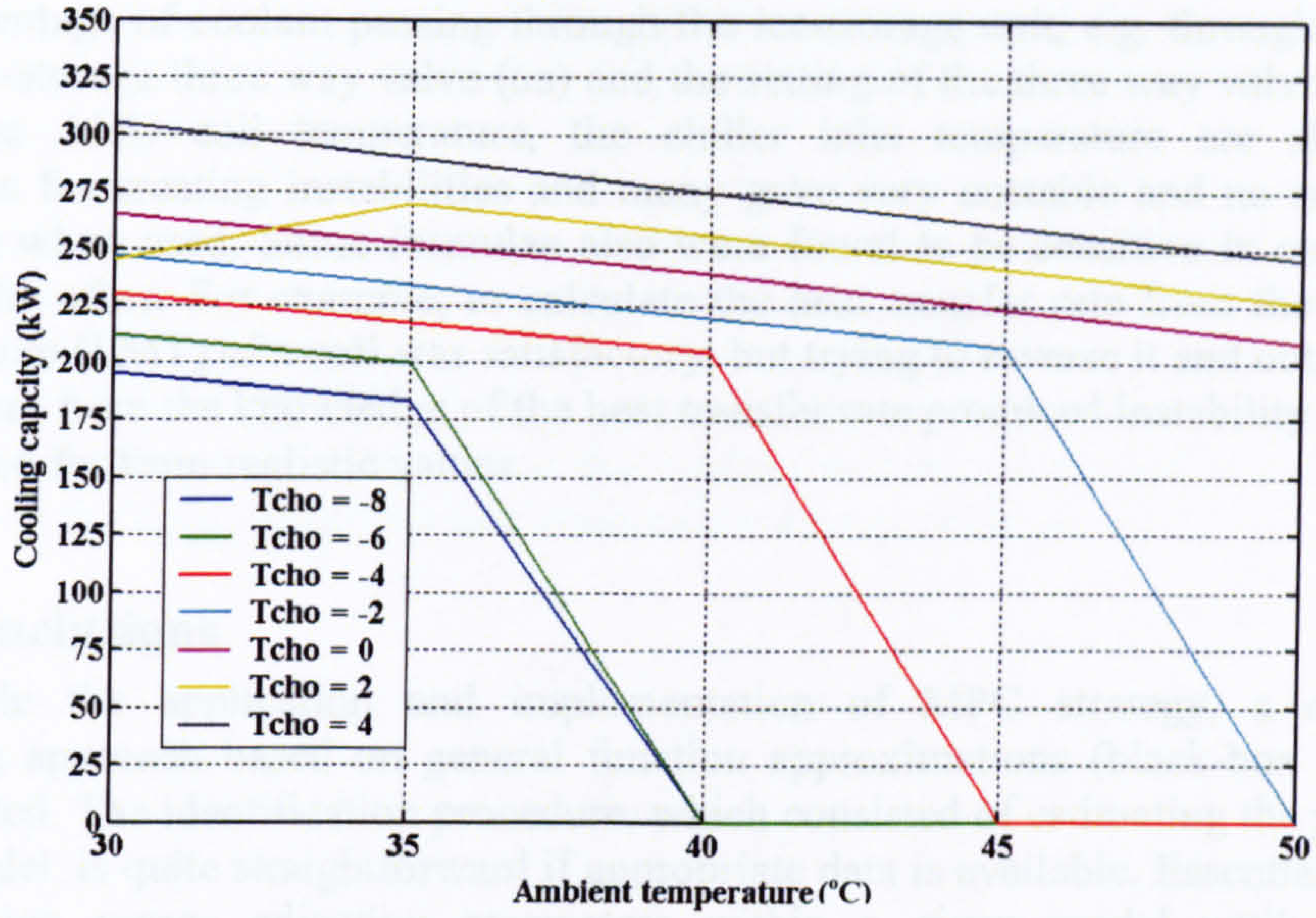

Figure 6.12 Chiller cooling power vs. the ambient temperature

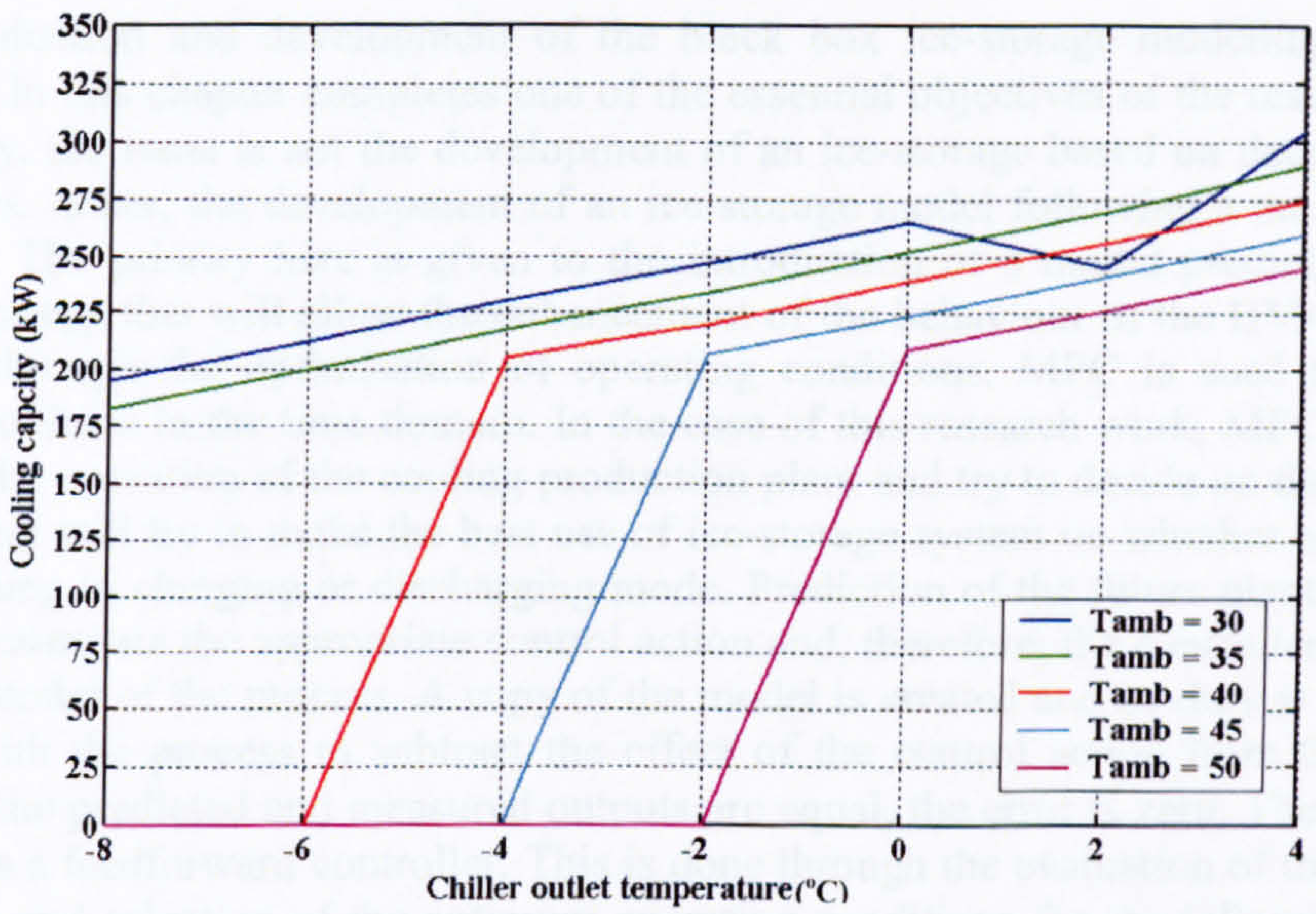

Figure 6.13 Chiller cooling power vs. the chiller outlet temperature

Consequently, the models were reconfigured to utilise tabulated data and a table look-up method was used. This had the advantage of restricting the results to those in the tables. Another complication related to the output of the simulink simulation, which, because of the various constraints imposed, showed serious repetitive and sudden jumps in the output to meet the imposed restriction in the variables. This behaviour is not uncommon in simulink models. However, this was deemed to be completely unsatisfactory when a smooth optimisation is required from the combined building_chiller_ice-storage model. This problem was solved by judiciously smoothing the building simulink output. Another interesting case to mention is the choice of the control variables. As the problem is non-linear, the problem sensitivity to different control inputs is not the same.

The percentage of coolant passing through the ice-storage unit, e.g. through the setting of the ice-storage three way valve (αs) and the setting of the three way valve (αa) at the AHU, the AHU coil temperature, the chiller inlet temperature are all probable candidates for creating instabilities and many gave very unstable and no convergence situations when used. Some formulae also were found to be sensitive in one direction and not the other. For example, to calculate the heat transfer rate from the Log-Mean Temperature (LMT) of a coil was satisfactory, but trying to reverse it and obtain the coil temperature from the knowledge of the heat transfer rate produced instability and swung the solution far from realistic values.

6.7 Conclusions

To enable the application and implementation of MPC strategy, a data-driven modelling approach based on general function approximations (black-box structures) was adopted. The identification procedure, which consisted of estimating the parameters of the model, is quite straightforward if appropriate data is available. Essentially, system identification means adjusting parameters within a given model until its output coincides as well as possible with the measured output.

The introduction and development of the black box ice-storage modelling approach described in this chapter completes one of the essential objectives of the research work. Eventually, the issue is not the development of an ice-storage based on detailed design procedures, rather, the development of an ice-storage model following a more practical approach. The priority here is given to the introduction of a model predictive control (MPC) strategy that will allow the enhancement of the behaviour of the HVAC plant as a whole through the optimisation of operating conditions. MPC is used for solving control problems in the time domain. In the case of this research work, MPC is used to optimise the operation of the cooling production plant and try to decide on the operation strategy that will try to make the best use of ice-storage system on whether to assign its duty as being in charging or discharging mode. Prediction of the future plant behaviour is used to compute the appropriate control action and, therefore, the controller requires a dynamic model of the process. A copy of the model is created and its duty is to work in parallel with the process to subtract the effect of the control action from the process output. If the predicted and measured outputs are equal, the error is zero. The controller operates as a feedforward controller. This is done through the evaluation of the previous conditions and selection of the optimum operating conditions for the following period. Upon that, the predictive control strategy would decide on which cycle of the cycles highlighted earlier to operate the system on.

MPC in the case of this research work is aiming at the optimisation of the cooling production process, hence, driving to the optimum operation of the cooling plant as a whole. The model does not involve neural networks for the prediction of the future demands. Rather, given data from the previous day or any other horizon that could be longer or shorter in duration, the MPC is able to predict on which best conditions to operate upon is and the amount of cooling to be produced and stored for next day. In other words, a neural network could have been utilised and the future demand could be predicted and upon that energy could be stored in the form of ice. However, it is believed that the advantage of utilising MPC is that it optimises the operation of the system in addition of making good use of the surplus cooling from the chiller during milder days to charge the storage a few hours before the need of more cooling during later hours on the same day.

Although the path for developing the integrated ice-storage HVAC plant with an MPC was thought to make the modelling approach simpler; yet, as the behaviour of such system with the several HVAC plant component is highly non-linear process, the development and testing evaluation of the modelling process took a considerable time. However, the advantage is that once the model has been developed, it can serve as a generalised model to represent other types of ice-storage models.

"A number of definitions exist for exactly what a sustainable design means for buildings. In essence, it involves a complete integrated building design that minimises the impact on the environment and use of non-renewable natural resources" ... Lawrence, 2004

Chapter 7

A Model Predictive Control Strategy for an Ice-Storage Assisted HVAC Plant

7.1 Introduction

The main objective of this research work is to arrive at the optimum operation of an ice-storage assisted HVAC system. Optimisation is conducted through the utilisation of a model predictive control strategy that targets the optimum operation conditions for the cooling production plant to operate upon. Here, the model predictive controller acts as a feed forward controller to iterate and predict the optimum operating conditions of the HVAC plant. This strategy replaces operating the ice-storage system in association with the plant that is based on an already set time table schedule plan. The model predictive controller aims at specifying which operation strategy is best to operate at a specific time, based on the cooling plant operating conditions. Through processing the system parameters and operating conditions that are dynamically varying, the MPC after going through many iterative processes has to decide on whether to operate on a positive set temperature from the chiller, which means the system can be in cooling, or cooling and discharging. Likewise, if the MPC decides on operating the chiller to produce a below zero temperature, depending on the operating circumstances, then this will result in making the system operate on cooling and charging strategy.

In addition to cutting the peak day installed capacity by nearly 50% by removing the need for an extra chiller, the advantage of implementing such a strategy is to affirm that the cooling plant is meeting the full load operating conditions for most of the time during the cooling season. As Kuwait does not implement different time tariffs schemes, it is believed that such approach would be reasonable as there is no need for the system to interface with a time of use electricity charging scheme that is generally applied in privatised and public power sectors in the western countries. For the purpose of this research work, a peak day cooling load of 500 kW is used for the building model. Having a 50% share of the peak day cooling load, the chiller mentioned earlier in the previous chapter is selected with a capacity of approximately 305 kW. However, the chiller capacity is expected to vary with the variation of the ambient temperature and also the chiller outlet temperature. The ice-storage is assigned to provide the remaining cooling demand.

7.2 Preliminary Results

The primary objective of the model predictive controller is to enhance the performance of the system by the defined control variable, and deciding which measurement is best modulated to achieve optimum operation of the system. The performance of the system is characterised by the behaviour of several parameters. Looking at the system diagram presented earlier in Chapter 6, also Figure 7.1 below, a sense of the different performance measures can be produced. In Chapter 5, the main aim was to investigate and examine the different patterns of the electrical load with reference to the thermal behaviours of specific zones at different orientations and how this might affect the development of a building's environmental services control zoning. In this chapter, the effect of the different zones can also be emphasized. In order to predict the future behaviour of a process, a model of how the process behaves must be available. The initial simulink building zone model was used to provide the load variations that acted as a base for the model predictive control strategy implemented. This base model is capable of showing the dependence of the cooling load on the different variables such as weather conditions, occupancy, lighting, occupancy and non-occupancy periods.

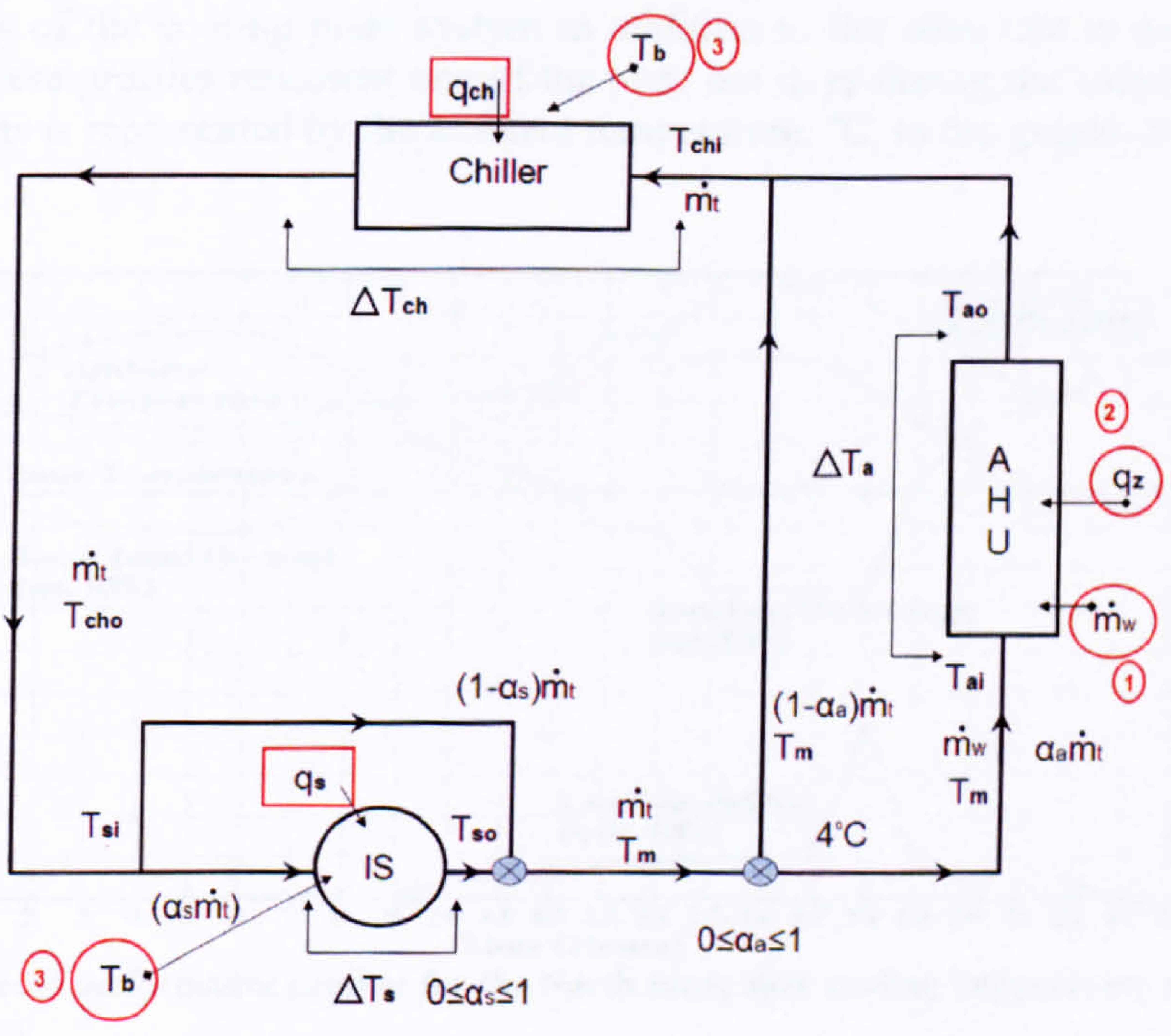

Figure 7.1 Layout of the HVAC plant with ice-storage

For the purpose of the new strategy, the simulink building model with AHU is link to a matlab algorithm that represents the same system in addition to the chiller and ice-storage. At this point the duty of the MPC is to update the system on an hourly basis and see how best it will behave upon the new measured values of the new introduced variables. On the contrary, the initial simulink model did not have a chiller component included. An assumed value of cooling coil water temperature was assumed for a fixed value of 5°C. As mentioned earlier in Chapter 6, the developed algorithm deals with a selected chiller model that is capable of operating with a temperature range between -8°C to 8°C. The algorithm that represents both the chiller and ice-storage unit are able to interact and dynamically operate with the AHU. The concept of prediction is presented by the repetition in the optimisation of the condition of the objective variable, Equation 7.1, over a 24 hour horizon extending from an initial future hour up to 24 hours.

$$q_z + q_{ch} + q_s = \text{Zero} \qquad \textbf{Equation 7.1}$$

The system is tested while running with a fixed zone cooling temperature set point at 24°C for all times. The second strategy was setting the zone temperature at 24°C during occupancy hours and at 28°C during non-occupancy hours. No attempts was taken to examine a system with a conventional cooling plant arrangement as it is believed that such system would need to provide instantaneous cooling for the building. In such cases, a chiller with a maximum capacity capable of meeting the peak day load of the year would need to be chosen. Results produced gave affirmation that the model is capable of dealing with the dynamic variation in the parameters it had to deal with. This can be clearly seen on the different profiles generated from the model and displayed in the results. The figures 7.2 to 7.9 below demonstrate the behaviour of the different components of the cooling plant system in addition to the zone that is demanding the cooling. These profiles represent one of the very hot days during the summer season in Kuwait. This is represented by the ambient temperature, °C, in the graphs below.

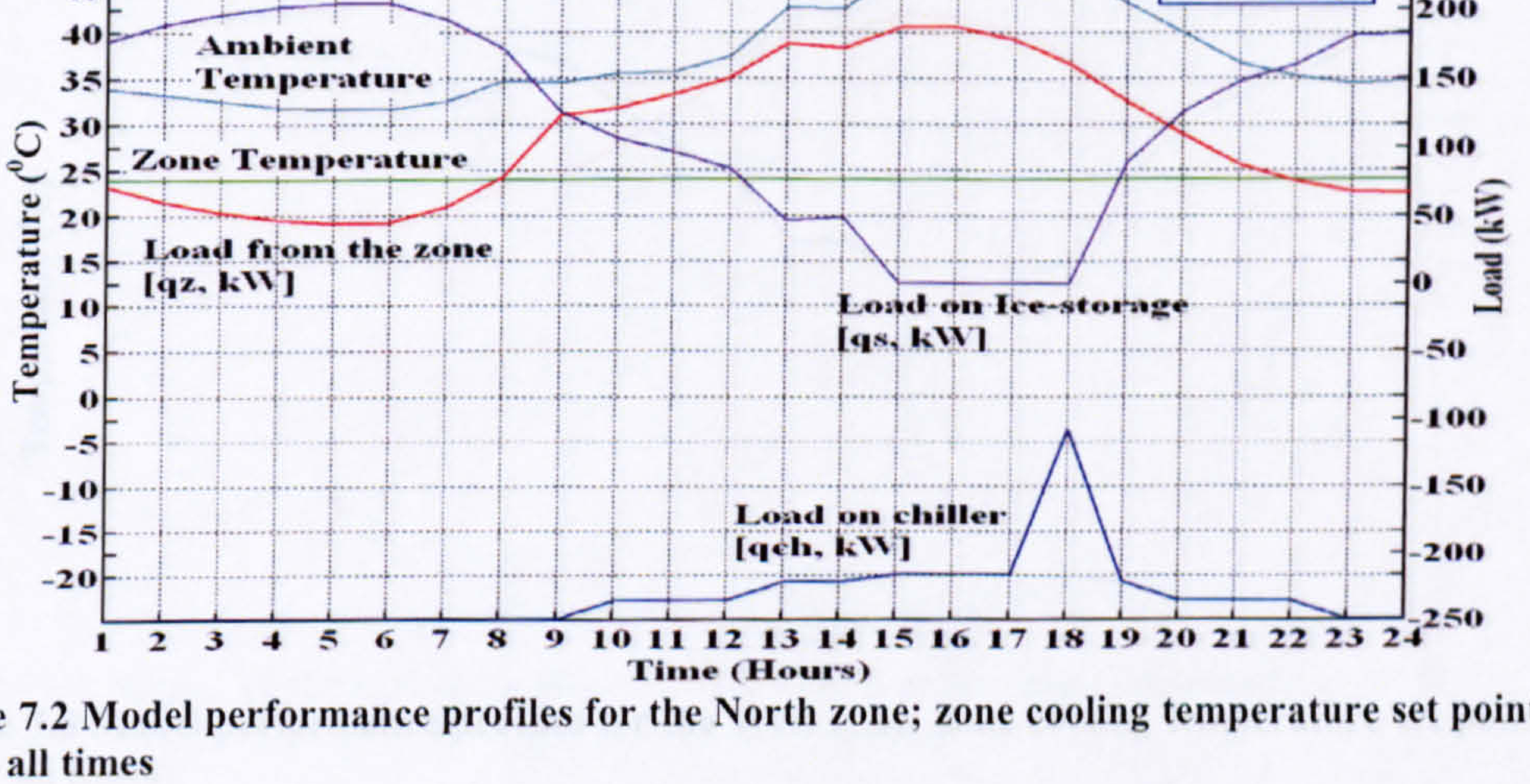

Figure 7.2 Model performance profiles for the North zone; zone cooling temperature set point at 24 °C for all times

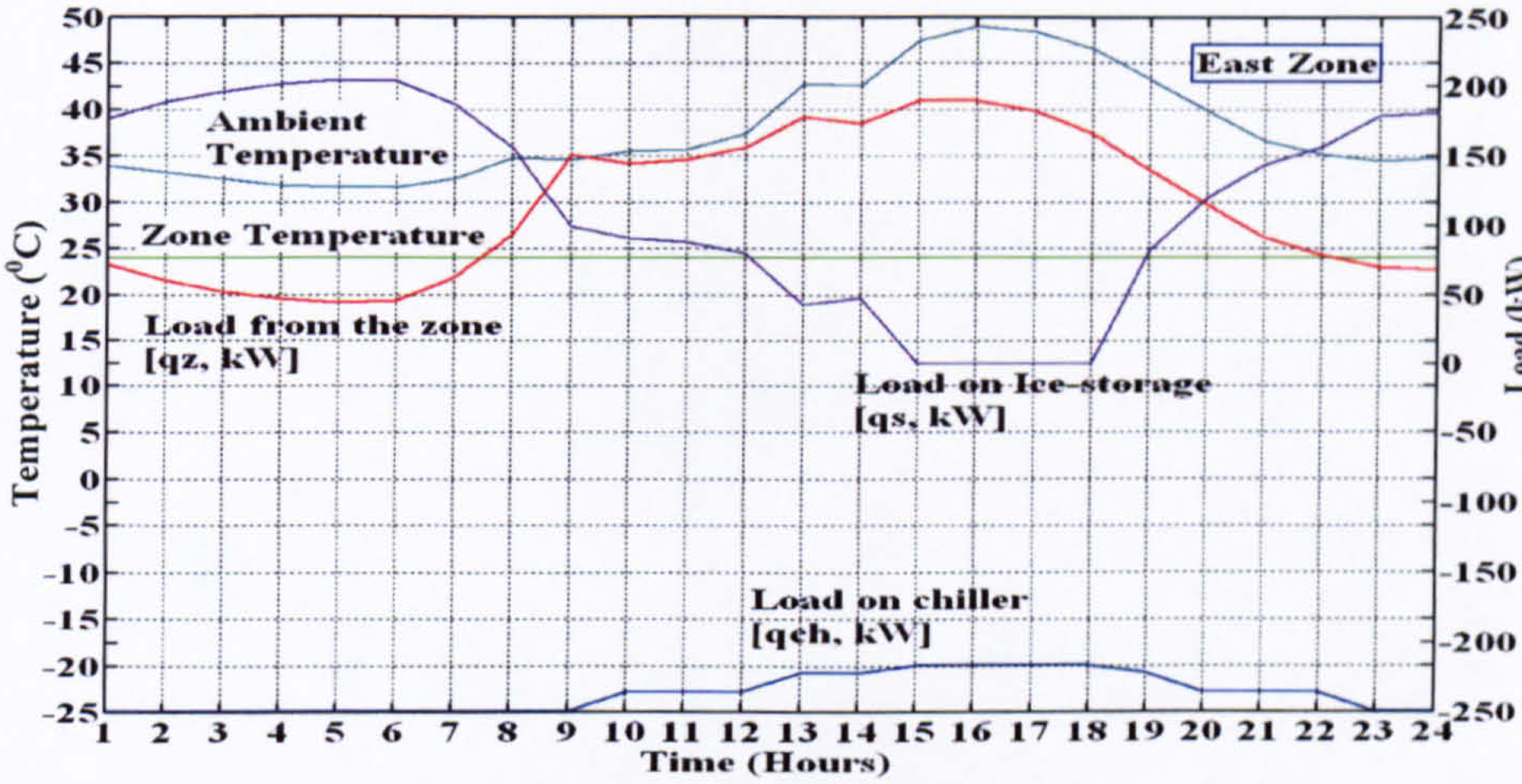

Figure 7.3 Model performance profiles for the East zone; zone cooling temperature set point at 24 °C for all times

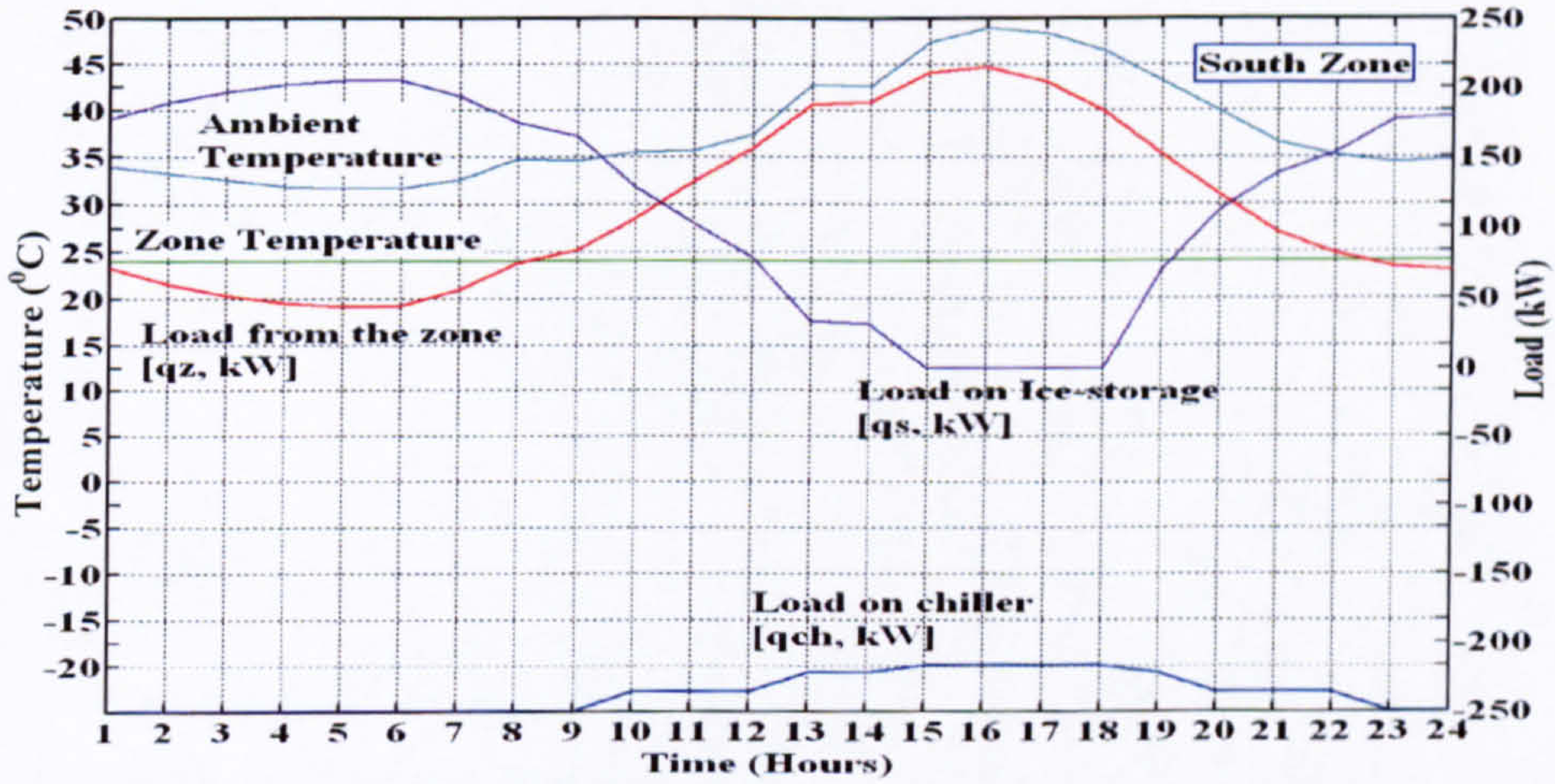

Figure 7.4 Model performance profiles for the South zone; zone cooling temperature set point at 24 °C for all times

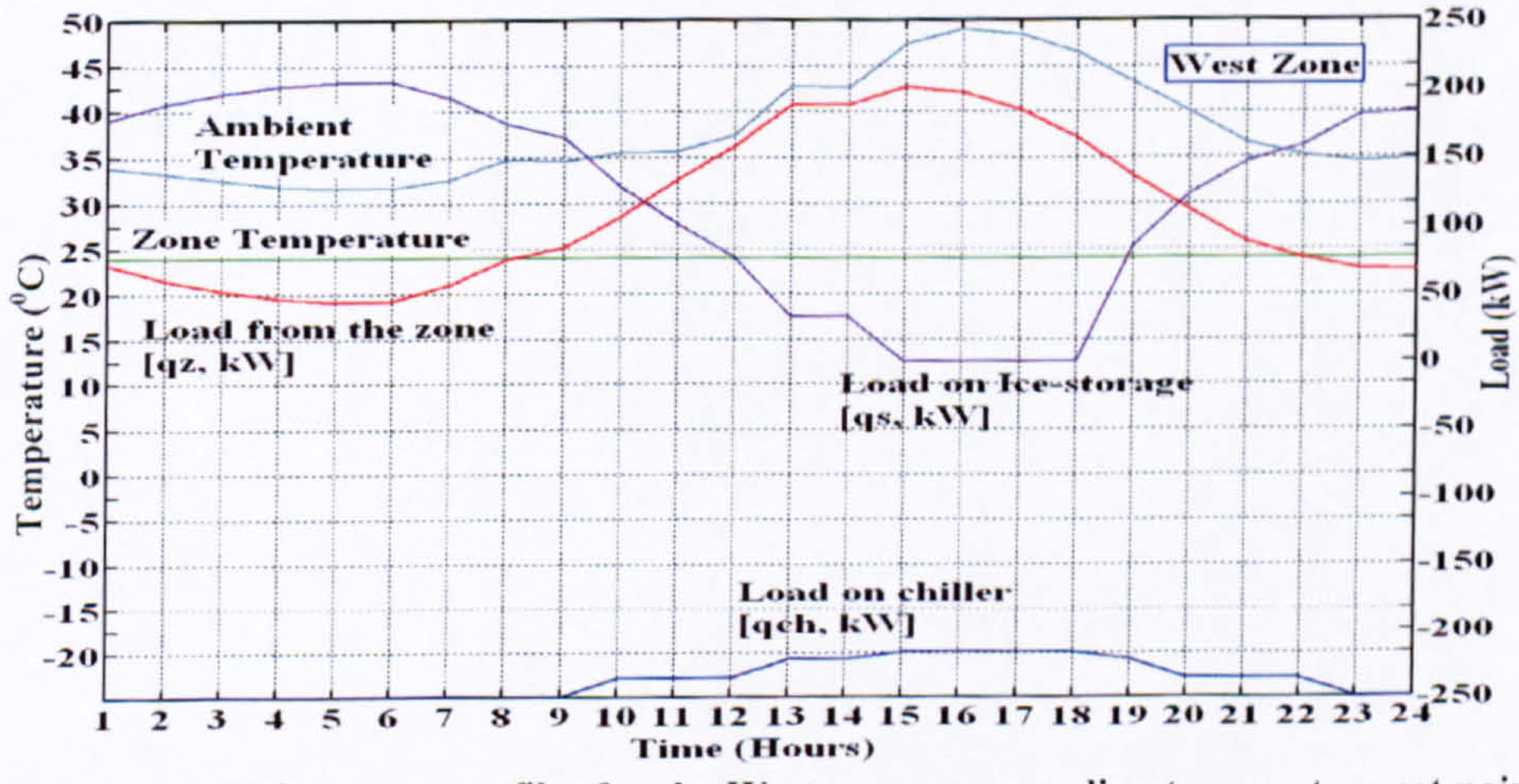

Figure 7.5 Model performance profiles for the West zone; zone cooling temperature set point at 24 °C for all times

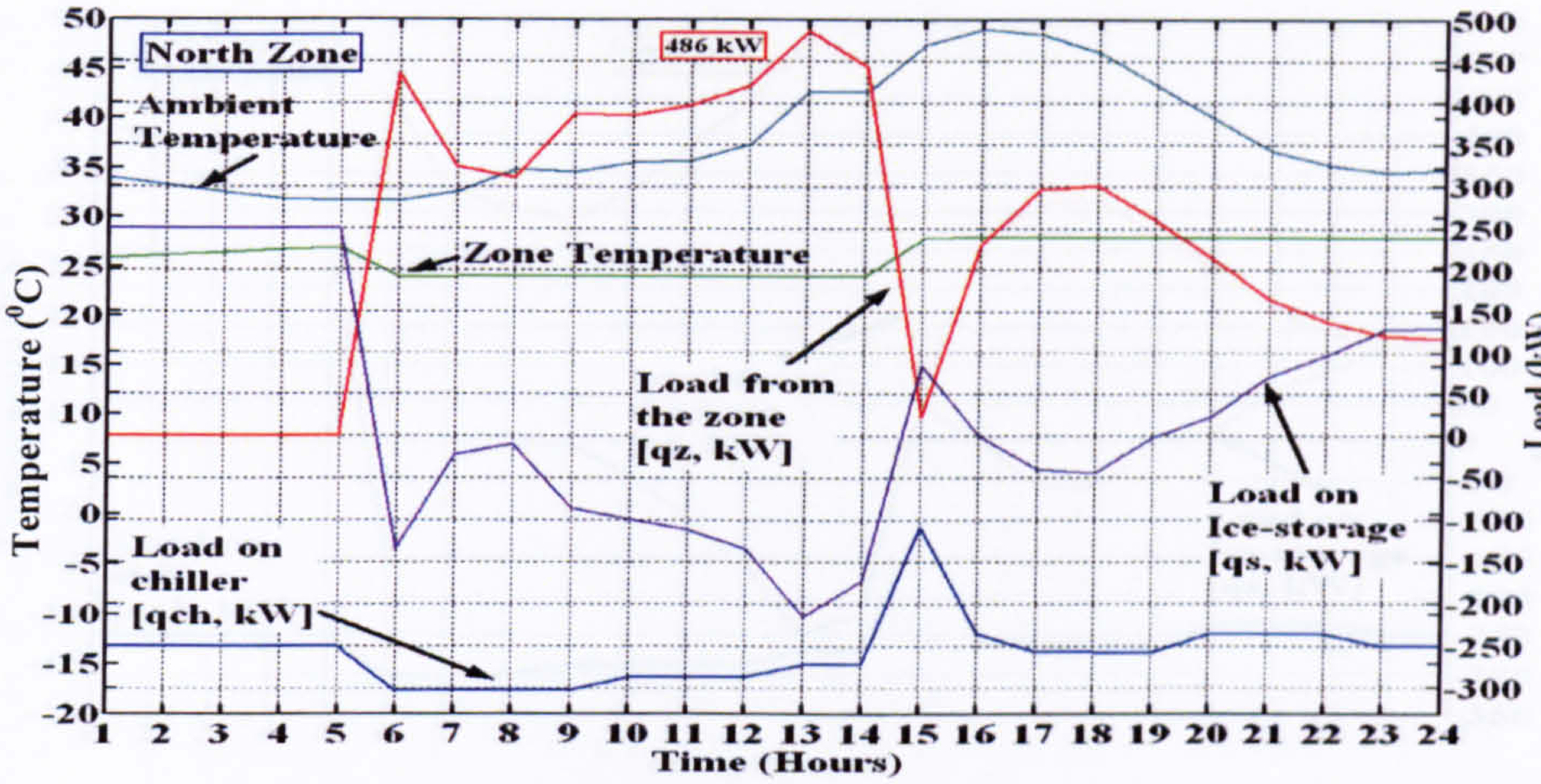

Figure 7.6 Model performance profiles for the North zone; zone temperature at 24 °C during occupancy hours and at 28 °C during non-occupancy hours

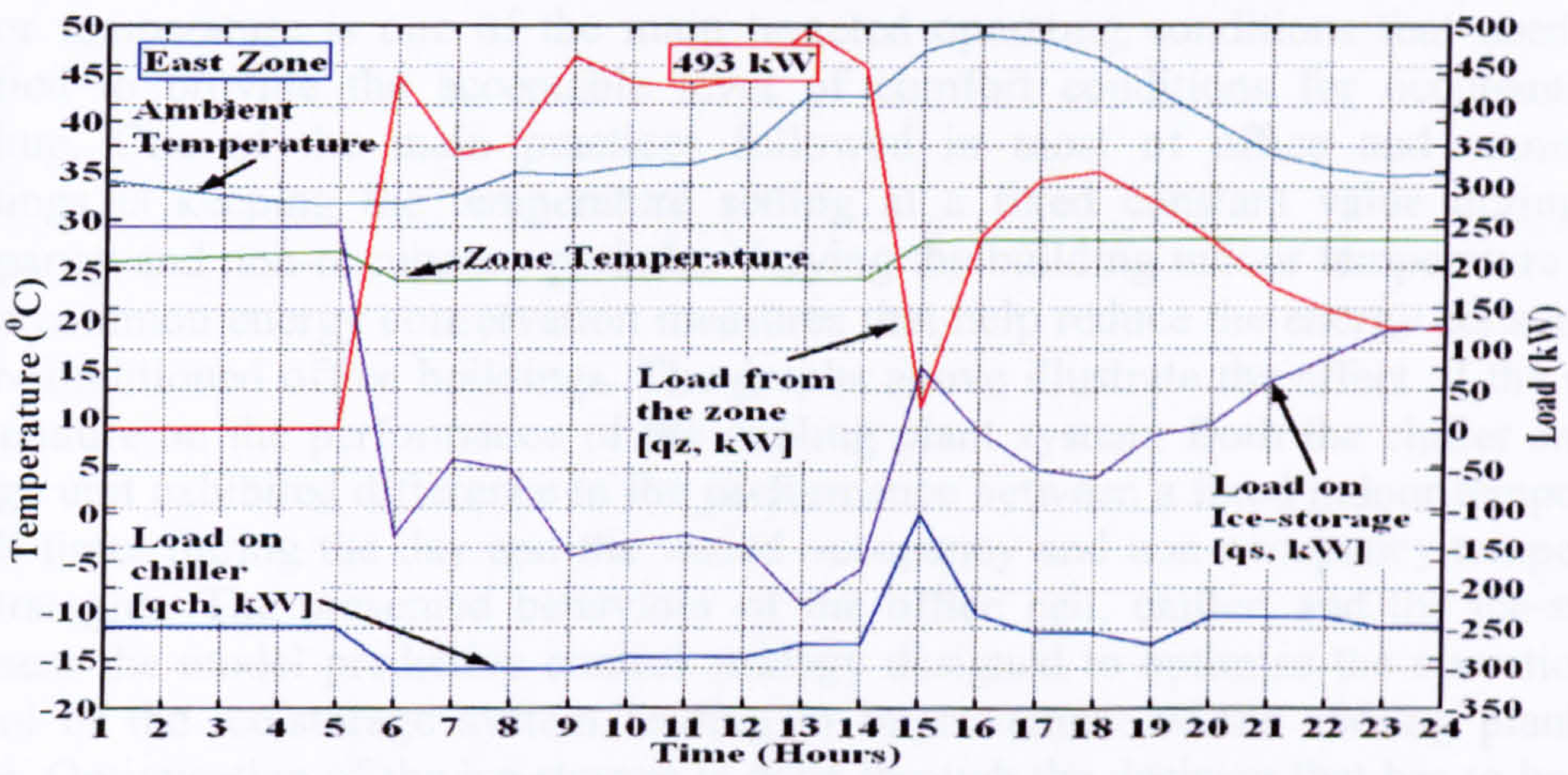

Figure 7.7 Model performance profiles for the East zone; zone temperature at 24 °C during occupancy hours and at 28 °C during non-occupancy hours

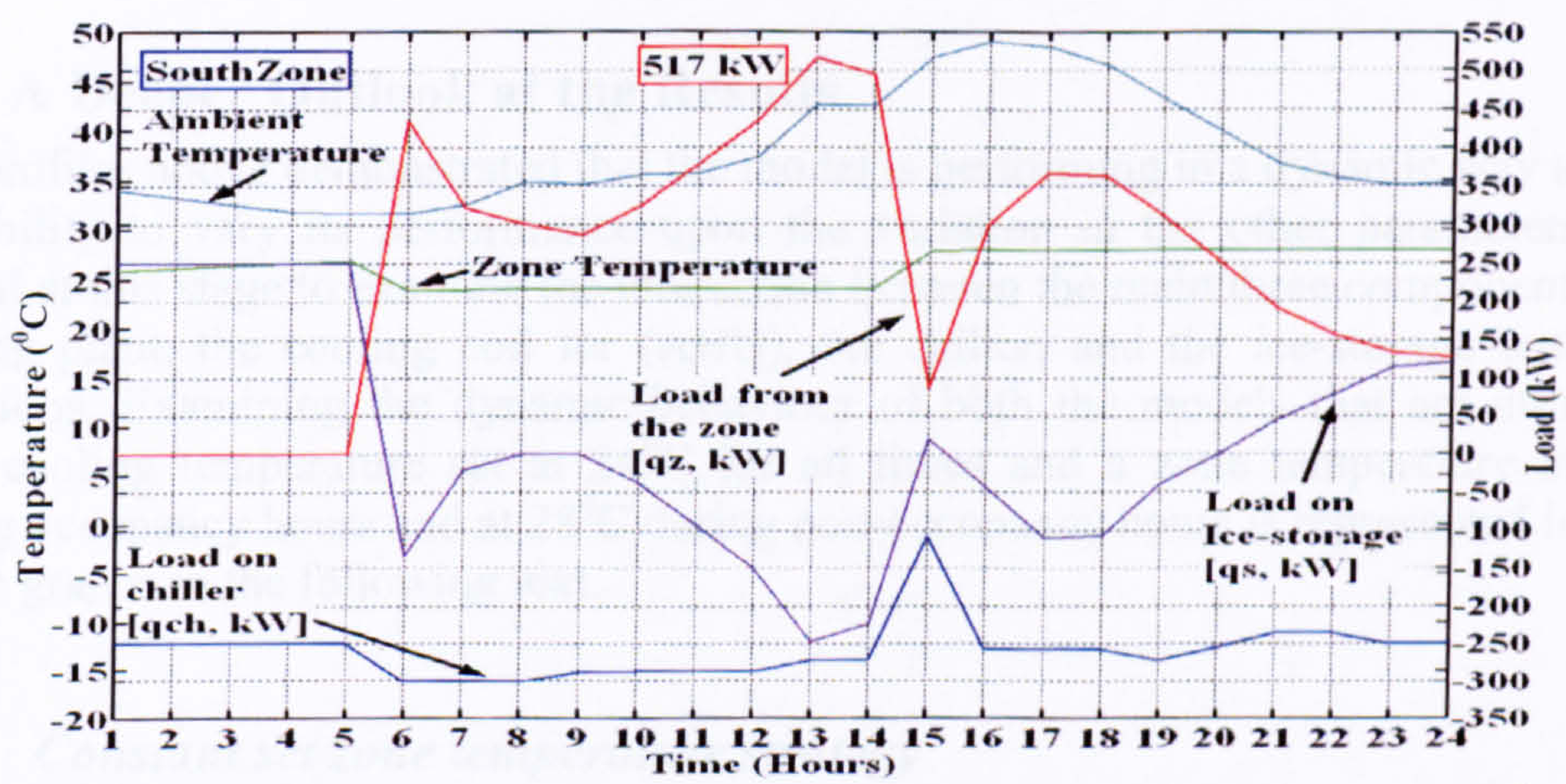

Figure 7.8 Model performance profiles for the South zone; zone temperature at 24 °C during occupancy hours and at 28 °C during non-occupancy hours

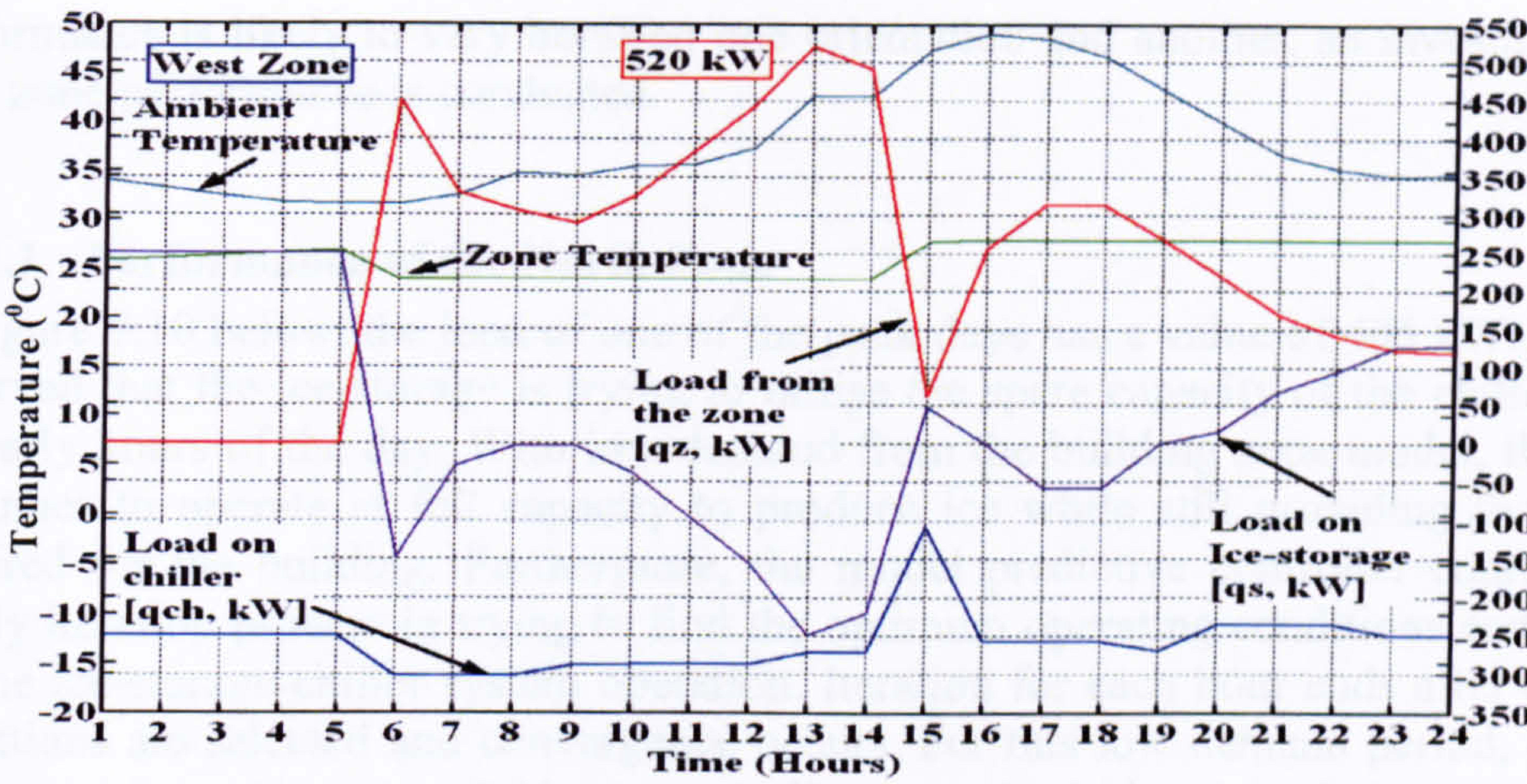

Figure 7.9 Model performance profiles for the West zone; zone temperature at 24 °C during occupancy hours and at 28 °C during non-occupancy hours

Indoor temperature is one of the main targeted operating conditions that need to be satisfied to provide the acceptable level of comfort conditions for occupants in a building. One of the main practices followed in most of office and commercial buildings is keeping the temperature setting at a fixed constant value during both occupancy and non-occupancy periods. Varying the building indoor temperature is one of the common energy conservation measures that help reduce the energy consumption in air-conditioned office buildings. The graphs above illustrate the effect of the indoor temperature on the performance of the cooling plant system. Both the chiller and ice-storage unit exhibited difference in the performance between a fixed indoor temperature for all times during the day and the varied occupancy and non-occupancy temperature set strategies. The presented behaviour of the office cell, chiller, and the ice-storage represent the model predictive control strategy designed to optimise the operation and control of the ice-storage system leading to improvement of the cooling plant as a whole. Optimisation of the ice-storage is done through the decision that has to be made of whether to charge or discharge the ice-storage system.

7.3 A Deeper Outlook at the Results

The profiles above demonstrated that the model is performing in a dynamic way and has the ability to vary its performance upon the variation in the other parameters. It is crucial at this stage to examine the interaction between the main three component of the cooling plant, the cooling coil for (AHU), the chiller, and the ice-storage with such variations. Examining the dynamic behaviour of both the models that are utilising a zone cooling temperature set at 24°C for all times and a zone temperature at 24°C during occupancy hours and at 28°C during non-occupancy hours is represented initially by the graphs in the following text.

7.3.1 Constant set zone temperature strategy

Looking at the profiles for the different zones, for selected summer days, the variation in the peak load occurs mainly between the hours of 14.00 and 16.00. As system performance is likely to vary between one orientation and another, an investigation for each zone performance is conducted.

7.3.1.1 Performance of the North Zone

In Figure 7.10 below, the load of one of the peak days has a value of 405 kW. It can be observed that the ice-storage is trying to utilise the spare capacity of the chiller during the early hours of the day. With low demand from the building zone model, the chiller continues to operate at full capacity to produce ice while still providing the cooling required for the building. Furthermore, the model predictive controller continues the hourly iteration process in trying to find the optimum operating conditions and strategy for the ice-storage-chiller system operation. Iteration for each hour ends after optimum conditions are selected and convergence occurs. For this low demand period, charging the ice-storage with the available spare cooling capacity is the elected strategy. This not only can be observed from the profile of the ice-storage load profiled; it can also be noticed from the behaviour of the mixing temperature (T_m), in Figure 7.11. During these hours when the ambient conditions are cooler, it is observed that the mixing temperature has low values. This is the period defined with charging process. At approximately 10.00 hours the mixing temperature rises and cooling continues, however, this time with system in discharging mode. This is coming out from the logic the MPC is applying to optimally control and run the system.

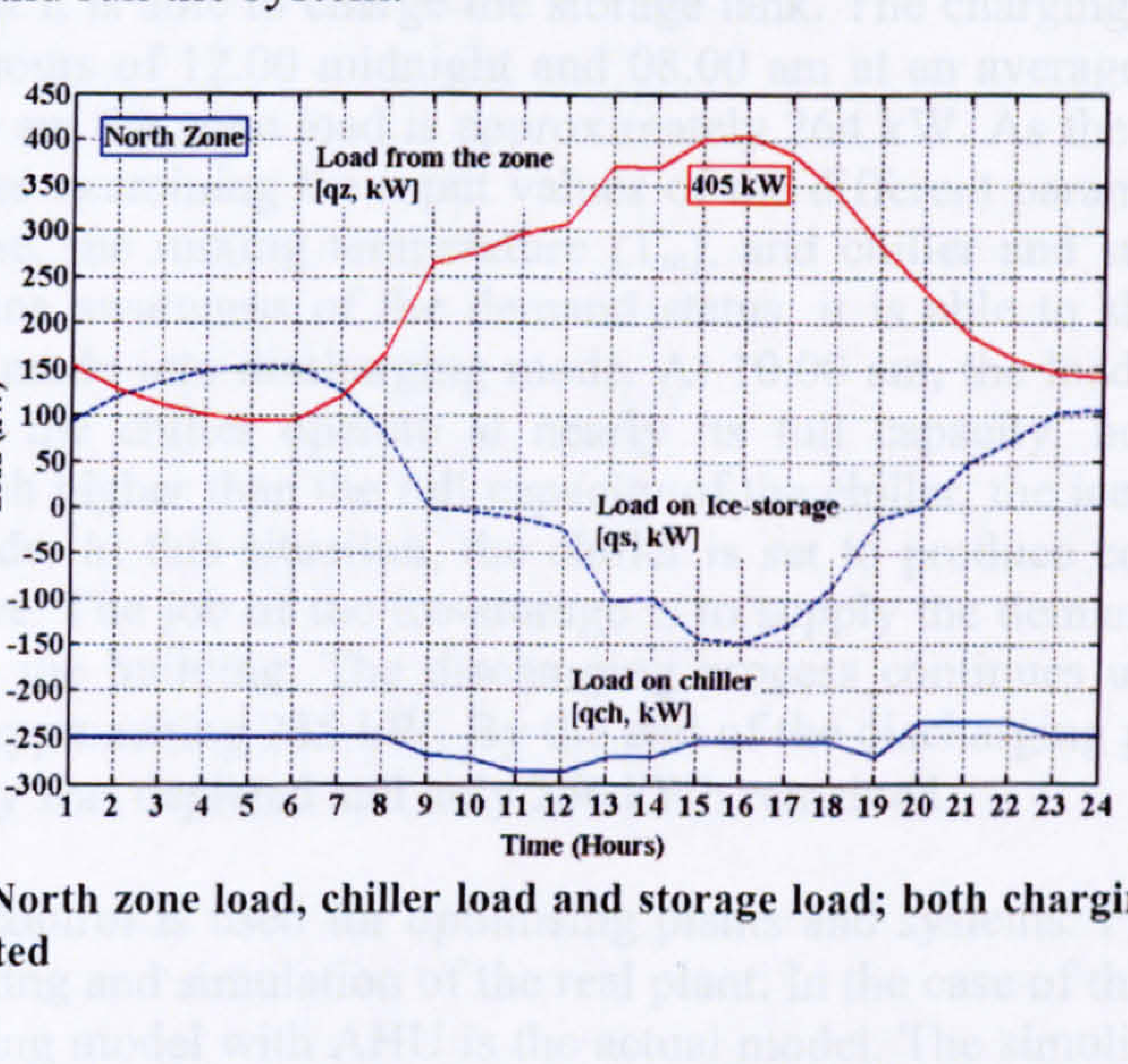

Figure 7.10 North zone load, chiller load and storage load; both charging and discharging are represented

Moreover, the status of the ice-storage gives a good indication of the process, Figure 7.11. The status of the ice-storage represents the amount of energy, in the form of ice, charged in the storage tank that will be available for melting (discharge) at a later period. The figure shows the ice build up in the tank starting from 12.00 midnight. The charging continues until 08.00 hours in the morning. At 09.00 hours, the ice-storage load (q_s) is equal to zero. This means that neither charging nor discharging is experienced during that hour. Between the hours of 08.00 am and 09.00 am, the ice-storage status is at its peek. At 10.00 am, the system switches to discharging as the demand rises beyond the capacity of the chiller. Discharging stays in action until 19.00 hours and then the system switches back to cooling and charging again.

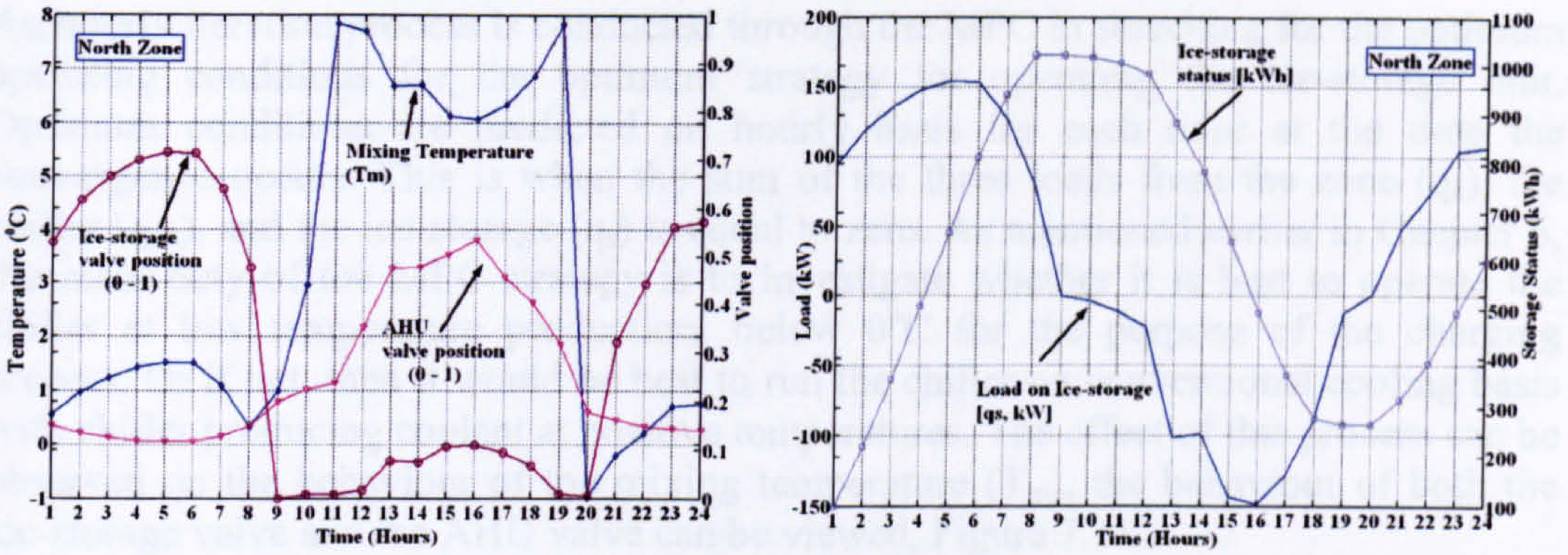

Figure 7.11 North zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

The three graphs above illustrate a complete sequence that explains what is occurring during different periods of time. For instance, the load profiles in Figure 7.11 show that during the early hours of the day, when there is low demand, the chiller is assigning part of its capacity to provide cooling to the space. A decision is made by the MPC strategy. At the same time, with the available spare capacity the chiller is working at low temperature so that it is able to charge the storage tank. The charging process is taking place during the hours of 12.00 midnight and 08.00 am at an average charging rate of 128 kW. At 09.00 am the zone load is approximately 264 kW. As the model predictive controller continues examining the input values of the different parameters such as the load from the zone, the mixing temperature (T_m), and chiller and storage data every hour so it maintains awareness of the demand status, it is able to shift directly from being in charging mode into discharging mode. At 10.00 am, the load increases to 276 kW which makes the chiller operate at nearly its full capacity, however, with the demand being much higher than the full capacity of the chiller, the ice storage switches into discharge mode. In this situation, the chiller is set to produce coolant at positive cooling temperature. The job of the ice-storage is to supply the demand that the chiller fails to provide to the building. The discharging process continues until 20.00 hours, where the load is approaching 235 kW. By the end of the discharging process 757 kWh of the stored energy was depleted and only 266 kWh remained.

Model predictive control is used for optimising plants and systems. Prediction is done through the modelling and simulation of the real plant. In the case of this research work, the simulink building model with AHU is the actual model. The simulink model is then connected to the simulated plant to provide the next day optimum operating conditions. Supplying the model with the present system inputs conditions initially, it will then predict the following time horizon period upon that. For a system with MPC, predicting the optimum operating conditions can be for a period of as short as one hour. In such cases a short time horizon can be targeted. In the case of a cooling plant with an ice-storage associated with it, a longer time horizon that falls between 12 to 24 hours must be chosen. As energy needs to be stored in the ice-tank; charging process is usually expected to take minimum of few hours period to store energy in the tank. While seeking for next day optimum operating conditions, the MPC provides prediction of next day load through the simulated system.

An hourly iteration process is conducted through the MPC in searching for the optimum operating conditions for the optimum strategy for operating the ice-storage unit. Optimum conditions are predicted on hourly basis for each hour at the time the convergence occurs. This is when the sum of the three loads from the zone (q_z), the chiller (q_{ch}), and the ice-storage (q_s) is equal to zero. As mentioned earlier in Chapter 6, the main duty of the MPC strategy is to investigate whether it is best to operate the chiller at low temperature production, below 0°C for the purpose of the charging process. Or if not, then it would be best to run the chiller on conventional cooling basis with chiller producing coolant at positive temperatures. The effect of this process can be observed on the behaviour of the mixing temperature (T_m), the behaviour of both the ice-storage valve and the AHU valve can be viewed, Figure 7.11.

Table 7.1 North zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	154.5	-249.5	95	100	0.6	0.5	0.2
2	129.2	-249.5	120.3	220.3	1	0.6	0.1
3	112.7	-249.5	136.8	357	1.2	0.7	0.1
4	100.9	-249.5	148.6	505.6	1.4	0.7	0.1
5	95	-249.5	154.5	660.1	1.5	0.7	0.1
6	96	-249.5	153.5	813.6	1.5	0.7	0.1
7	121.6	-249.5	127.9	941.5	1.1	0.6	0.1
8	168	-249.5	81.5	1023.1	0.3	0.5	0.2
9	264	-268	0	1023.1	1	0	0.2
10	276.3	-272.5	-3.8	1019.3	3	0	0.2
11	297.8	-286.5	-11.3	1008	7.9	0	0.2
12	309.1	-286.5	-22.6	985.4	7.7	0	0.4
13	373.1	-271.5	-101.6	883.8	6.7	0.1	0.5
14	370.4	-271.5	-98.9	784.9	6.7	0.1	0.5
15	399.9	-256.5	-143.4	641.4	6.1	0.1	0.5
16	404.8	-256.5	-148.3	493.1	6.1	0.1	0.5
17	384.1	-256.5	-127.6	365.5	6.3	0.1	0.5
18	343.4	-256.5	-86.9	278.5	6.9	0.1	0.4
19	283.8	-271.5	-12.3	266.3	7.8	0	0.3
20	234.7	-235.5	0.8	267	-1	0	0.2
21	186.9	-235.5	48.6	315.7	-0.2	0.3	0.2
22	161.7	-235.5	73.8	389.5	0.2	0.4	0.1
23	145.4	-249.5	104.1	493.6	0.7	0.6	0.1
24	142.2	-249.5	107.3	600.9	0.8	0.6	0.1

It is important to highlight that demand might grow above the capacity of an existing installation at some future time. The following example is created for the sake of such argument. If the load of one of the extreme peak days in summer is peaking at 514 kW, Figure 7.12, then at some point the cooling plant would be incapable of providing sufficient cooling during some hours of the day. As a start the model predictive controller has to decide on whether to operate and target a positive chiller outlet temperature or would it be best to operate at a negative chiller outlet temperature and start the charging process while providing cooling to the building at the same time. As the cooling process is starting with a low demand, then, rather than allowing the chiller to operate on part load basis, it is best if cooling and charging is put in action. In this instance it is assumed that the chiller is going to operate on full load operation basis.

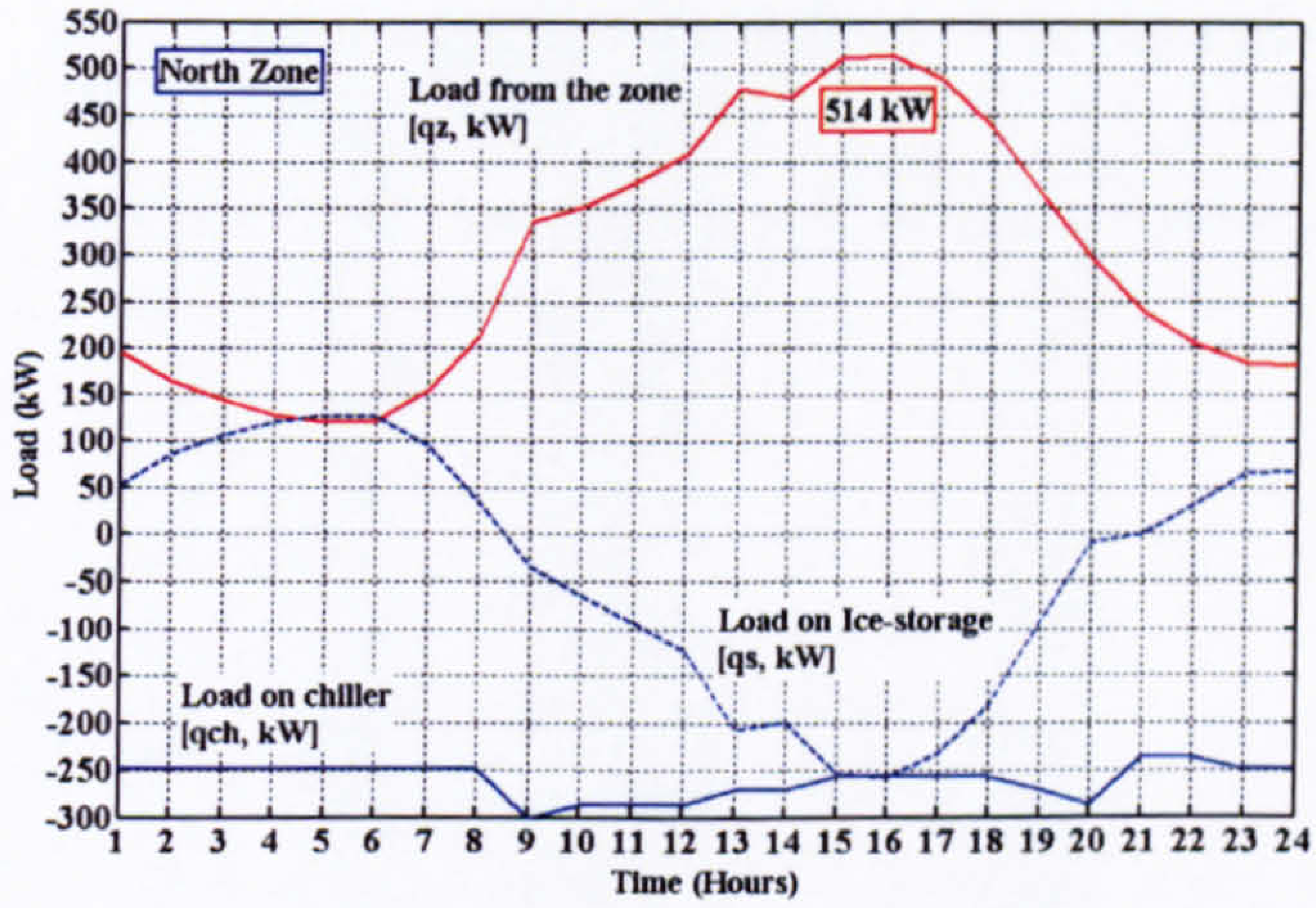

Figure 7.12 North zone load, chiller load and storage load; both charging and discharging are represented

It is predicted that the charging process will begin from the early hours of the day until 08.00 hours with a charging rate of 94 kW. At the time where the load begins to exceed the capacity of the chiller, the controller switches into discharging mode. The first charging period has a duration of eight hours, until 756 kWh of energy is stored. Starting at 09.00 hours, with the current load rising to 336 kW discharging is supposed to start and the discharging process is predicted to be operating for about nine hours. The discharging process continues until 20.00 hours, where the load is approaching 300 kW, see Figure 7.12. From that point, the storage tank is probably depleted at 21.00 hours. It is noticed that at 21.00 hours the load on the ice-storage is zero and cooling is provided by the chiller only. Table 7.2 presents the values of the case explained above.

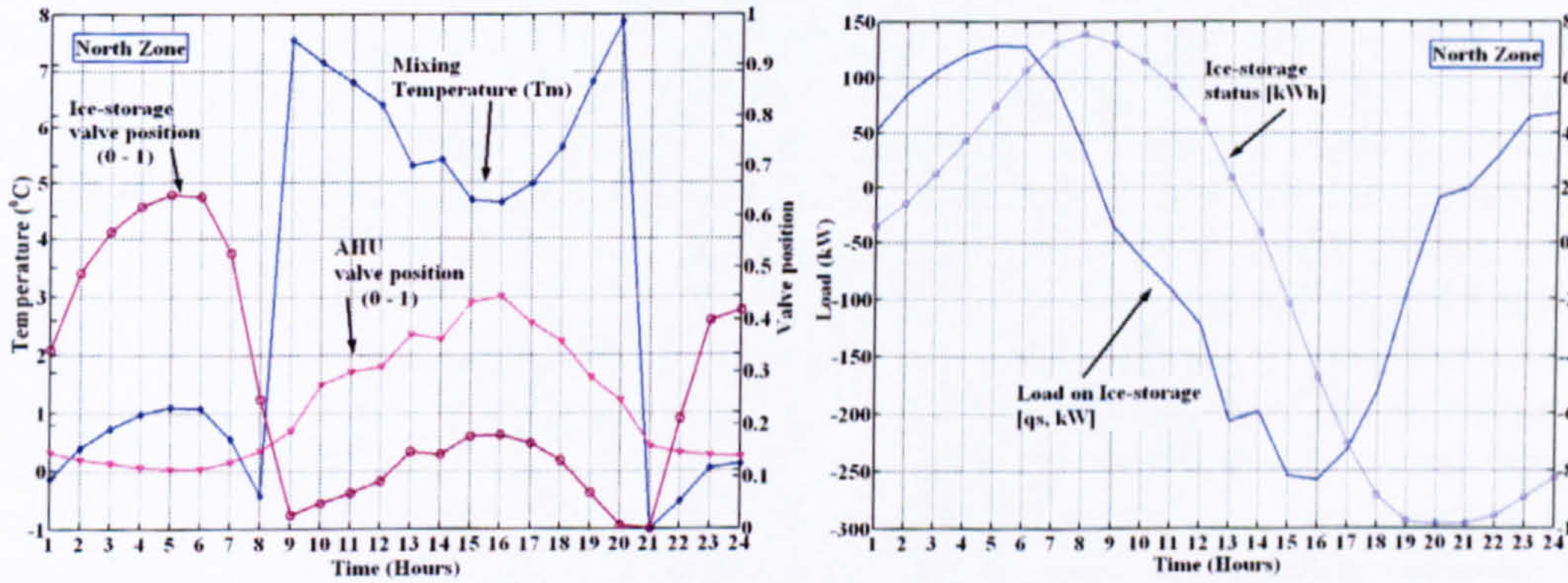

Figure 7.13 North zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

Table 7.2 North zone peak day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	196.6	-249.5	52.8969	57.8969	-0.1316	0.3434	0.147
2	164.42	-249.5	85.0768	142.9737	0.3967	0.49	0.1332
3	143.48	-249.5	106.021	248.9944	0.7406	0.5688	0.1265
4	128.46	-249.5	121.04	370.034	0.9872	0.619	0.1193
5	120.88	-249.5	128.617	498.6511	1.1116	0.6426	0.1156
6	122.21	-249.5	127.293	625.9439	1.0898	0.6385	0.1154
7	154.72	-249.5	94.7834	720.7273	0.5561	0.5279	0.1288
8	213.78	-249.5	35.7223	756.4496	-0.4135	0.2488	0.1506
9	336.44	-301.5	-34.9446	721.505	7.545	0.0278	0.1895
10	351.35	-286.5	-64.8526	656.6524	7.1556	0.0507	0.277
11	378.53	-286.5	-92.034	564.6184	6.8017	0.0708	0.302
12	409.58	-286.5	-123.082	441.5361	6.3974	0.093	0.3107
13	477.84	-271.5	-206.343	235.1935	5.3133	0.1487	0.3737
14	469.53	-271.5	-198.034	37.1599	5.4215	0.1434	0.3638
15	510.71	-256.5	-254.206	-217.046	4.6901	0.1785	0.4349
16	514.04	-256.5	-257.543	-474.589	4.6466	0.1805	0.4468
17	487.77	-256.5	-231.275	-705.864	4.9886	0.1644	0.3964
18	437.1	-256.5	-180.599	-886.4634	5.6485	0.1321	0.3606
19	362.49	-271.5	-90.9861	-977.4495	6.8153	0.0701	0.2913
20	295.77	-286.5	-9.2713	-986.7208	7.8793	0.0075	0.2464
21	237.86	-235.5	0	-986.7208	-1	0	0.1586
22	205.86	-235.5	29.6438	-957.077	-0.5133	0.2119	0.1462
23	185.09	-249.5	64.4108	-892.6662	0.0575	0.3999	0.1406
24	181	-249.5	68.5014	-824.1648	0.1246	0.4188	0.1385

The above example illustrated that for the discharge period of thirteen hours, discharging was taking place at an average discharge rate of 134 kW. The discharging process that is predicted to take place between the hours of 08.00 and 20.00 hours highlights some deficiency in the system. For a discharge period of thirteen hours stored energy of 1743 kWh is needed. However, starting to charge the system at 12.00 am until 08.00 am allows only storing the amount of 756 kWh of stored energy in the form of ice. In such situations, a higher charging rate is one of the options that can be highlighted. This indicates that a need for an additional chiller exists or that the charging process should have started earlier. The question to ask is, would providing an additional chiller be an energy efficient option? The answer could be no, however, for every cooling plant installed in an office building or large commercial building, a spare chiller is installed to be used as a stand by chiller in case the main chiller malfunctions. Another option would be to allow the system to start utilising a few hours of the previous day to start the charging process. If the last few hours of the previous day would have similar loads for example as the hours in the table above, period between 21.00 and 24.00 hours, then this would allow a bigger amount of stored energy to be produced. If the shortage in stored energy still exists, then a compromise between both highlighted options would be more suitable. As can be seen from Table 7.2, representative values of the profiles can be investigated. The results presented and discussed above represent one of the high peak days during the summer season. Upon that, both the chiller and the ice-storage had to operate at nearly their maximum capacity. In such conditions, if a building had one large ice-storage unit installed, then the whole storage should be charged to be able to provide its share of duty for cooling the building. Likewise, if several ice-storage tanks were installed, the same condition applies, as all the storage tanks would have to be fully charged to be able to provide its share of the required demand.

7.3.1.2 Performance of the East Zone

For the same day as that chosen for north zone, the load for the east zone approaches 410 kW. With available capacity from the chiller existing during the early hours of the day, the MPC sets the chiller to operate at a low outlet temperature and work to provide cooling and charging the ice-storage at the same time. This zone experienced slightly higher demands during the early hours of the day, as discussed earlier in Chapter 5, this was because of its orientation and that the east oriented zones in any building is the first to face the sun early during the day. This explains why the east zone would encounter slightly high peaks during early hours of the day.

Reviewing the graphs below, figures 7.14 and 7.15, illustrates the behaviour of the zone. The charging process starts while the demand is low and the chiller is able to provide both cooling and charging. For such conditions the model predictive controller assigns the task for the chiller to operate at low outlet temperature for the coolant to be able to freeze the water in the ice-storage tank. Again, this process ends by the time the load demands increases and it becomes larger than the chiller capacity. At 08.00 hours the amount of stored energy is equivalent to 977 kWh of ice. At 09.00 hours, the demand reaches 323 kW this affects the decision of the MPC, while it iterates and tries to select the optimum operation for the current hour. As the chiller is incapable of such current demand, then the model predictive controller commands the chiller to operate on positive coolant outlet temperature. At this phase, the mode becomes as cooling and discharging, where the stored energy is utilised to supply the additional demand that the chiller is unable to provide.

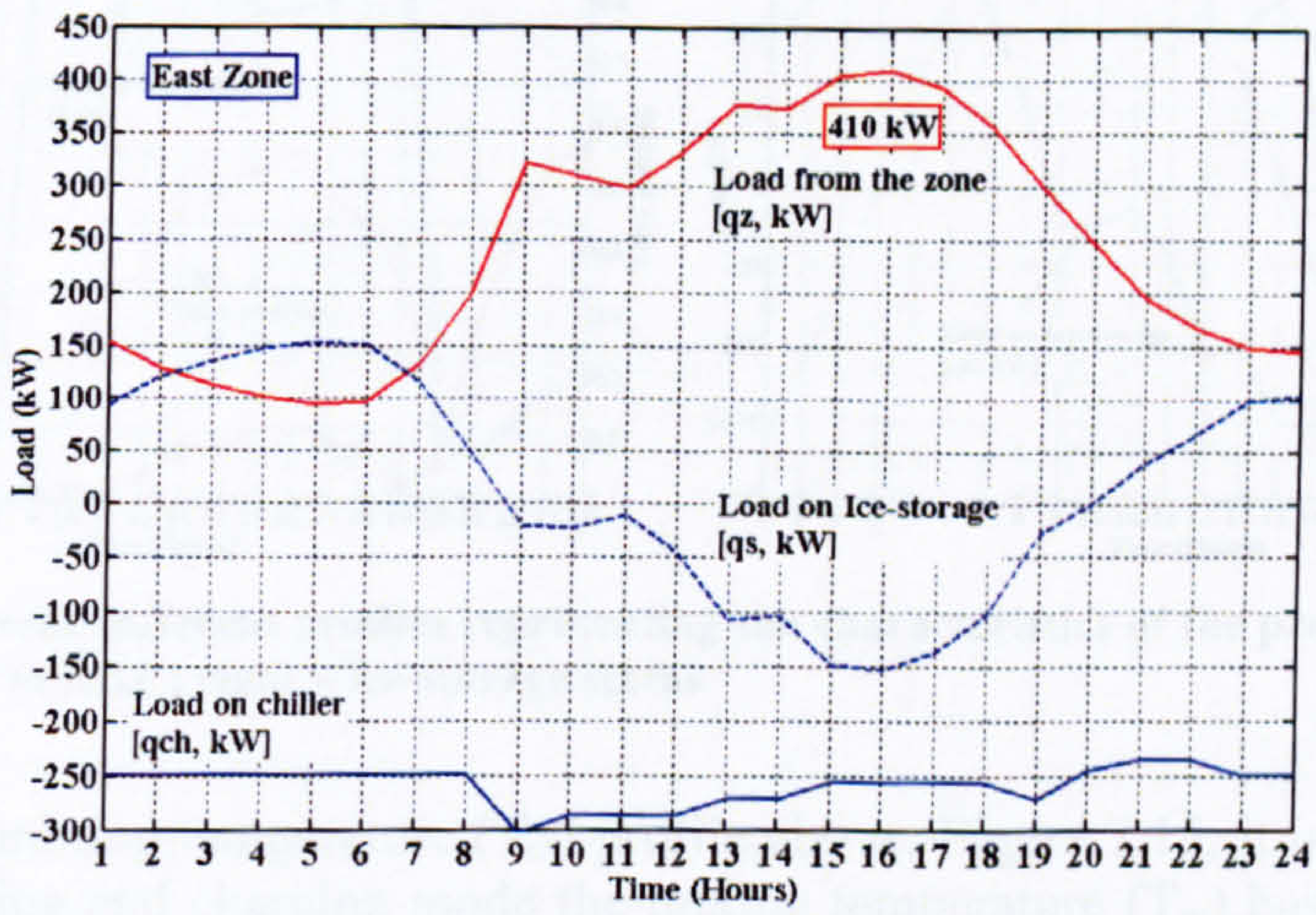

Figure 7.14 East zone load, chiller load and storage load; both charging and discharging are represented

Table 7.3 East zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	154.53	-249.5	94.9709	99.9709	0.5592	0.5286	0.1504
2	129.21	-249.5	120.2856	220.2566	0.9748	0.6166	0.1361
3	112.73	-249.5	136.7663	357.0228	1.2453	0.6667	0.1265
4	100.93	-249.5	148.5669	505.5897	1.4391	0.6997	0.1193
5	94.987	-249.5	154.5131	660.1029	1.5367	0.7155	0.1183
6	97.641	-249.5	151.8594	811.9623	1.4931	0.7086	0.1161
7	133.54	-249.5	115.9616	927.9239	0.9038	0.6025	0.1346
8	200.16	-249.5	49.342	977.266	-0.1899	0.3249	0.1648
9	322.96	-301.5	-21.462	955.804	7.7206	0.0172	0.2259
10	310.37	-286.5	-23.8674	931.9367	7.6892	0.0191	0.2504
11	298.36	-286.5	-11.855	920.0817	7.8456	0.0096	0.3356
12	332.36	-286.5	-45.8619	874.2198	7.4028	0.0363	0.363
13	378.93	-271.5	-107.428	766.792	6.6012	0.0819	0.4988
14	374.56	-271.5	-103.064	663.7284	6.658	0.0788	0.4945
15	405.28	-256.5	-148.783	514.9451	6.0627	0.1108	0.5278
16	409.8	-256.5	-153.297	361.6486	6.004	0.1138	0.56
17	393.25	-256.5	-136.746	224.9031	6.2195	0.1025	0.4868
18	357.66	-256.5	-101.164	123.7392	6.6828	0.0774	0.4449
19	299.35	-271.5	-27.8472	95.892	7.6374	0.0223	0.3475
20	247.62	-245.5	0	95.892	0	0.0546	0.1897
21	196.16	-235.5	39.3375	135.2295	-0.3542	0.2698	0.1667
22	168.38	-235.5	67.1217	202.3512	0.102	0.4125	0.1527
23	150.08	-249.5	99.4178	301.769	0.6322	0.5451	0.1462
24	145.76	-249.5	103.7351	405.5041	0.7031	0.5607	0.1433

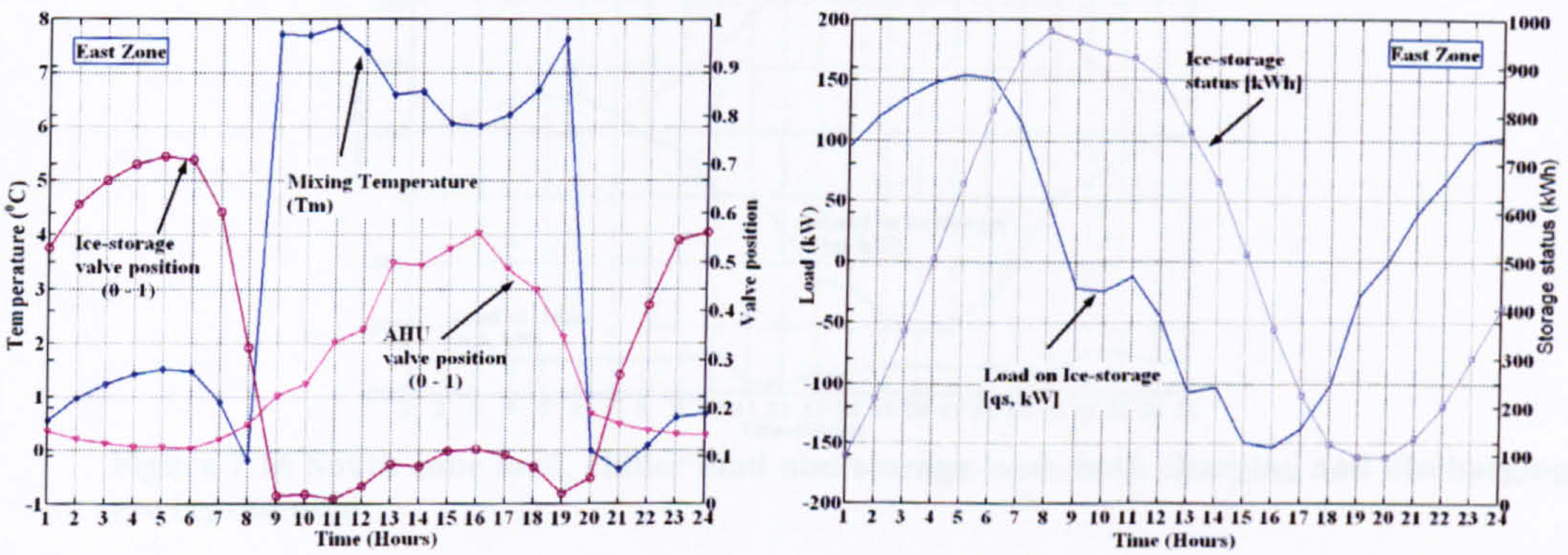

Figure 7.15 East zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

Examining the mixing temperature (T_m) profile above, Figure 7.15, it is noticeable that during the cooling and charging mode the mixing temperature (T_m) has low values. At the time the system switches to cooling and discharging mode, the mixing temperature (T_m) rises and tries to remain in the range between 6°C to 8°C. It is also evident that during the charging period, the ice-storage valve is mainly the one taking control of the process as it is nearly open up to 70% or more indicating that coolant is going through the storage tank to charge and freeze its contents. With the cooling and discharging process starting, the valves switch positions and the valve for the AHU mainly is taking the control. At the time the discharge process ends, it is noticed that out of the 977 kWh of stored energy, 882 kWh is depleted and only 95 kWh remained.

Looking at graph representing the ice-storage status, the figure shows the ice build up in the tank starting from 12.00 midnight. The charging continues until 08.00 hours in the morning. At 090.00 am, the system switches to discharging as the demand rises beyond the capacity of the chiller. Discharging stays in action until 19.00 hours and then the system switches back to cooling and charging again.

7.3.1.3 Performance of the South Zone

Looking at the representative graphs of the south zone, Figures 7.16 and 7.17, it can be observed that the same process keeps repeating for all the four zones. The peak load of the south zone occurs at 15.00 hours with the peak demand at 462 kW. Again, this is clearly the effect of its orientation. As the south zone faces the sun at the mid-day period the effect of solar gain and the increase in ambient temperature is reflected by the zone having higher demand values than the north and east zones. Cooling and charging starts at midnight and continues until 1106 kWh of energy is stored at 10.00 hours. Cooling and discharging begin at 12.00 noon up till 20.00 hours. However, out of the 1106 kWh of stored energy, the model predicted that a higher amount of 20 kWh was required ,which to some extent could be considered as small in value.

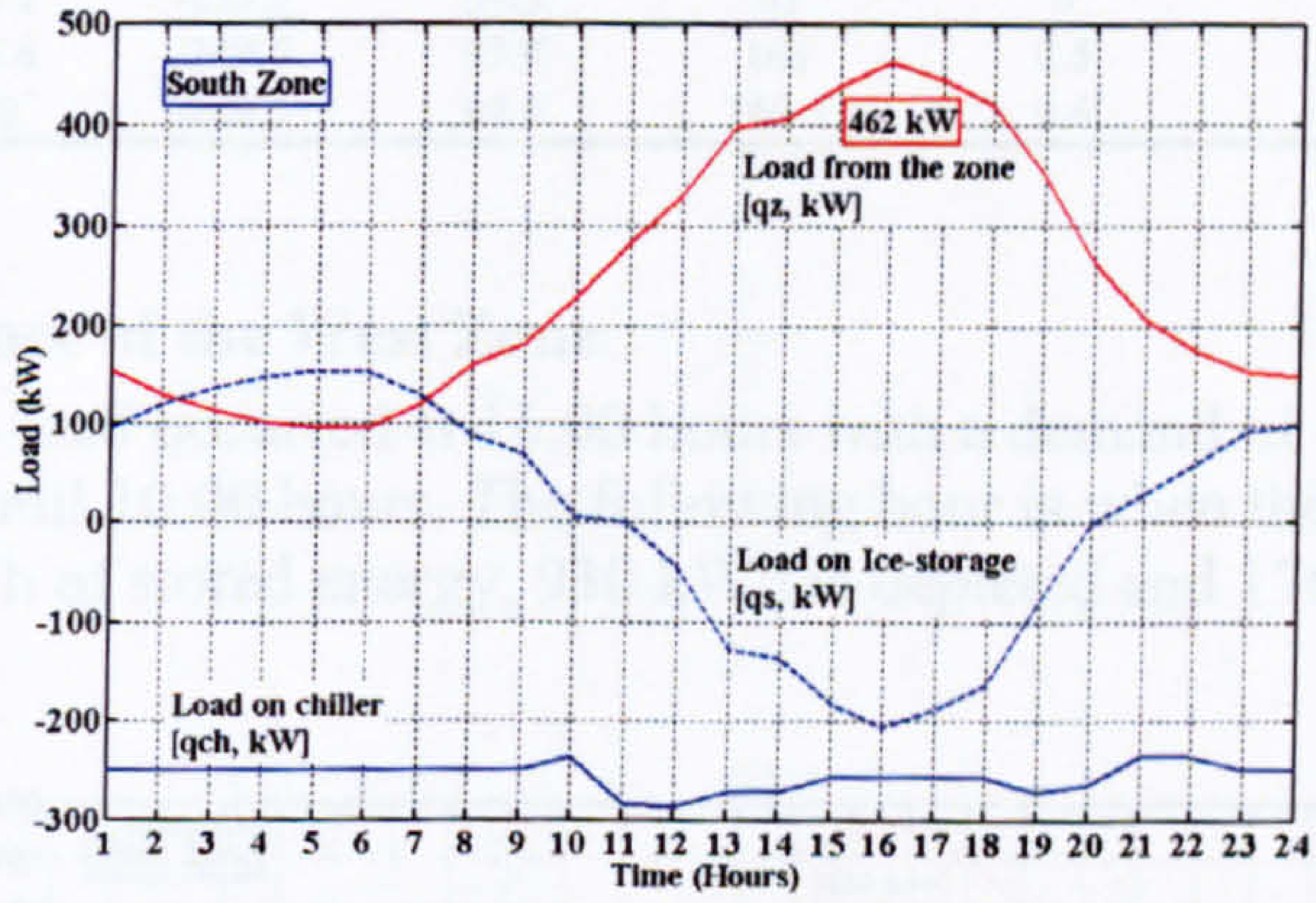

Figure 7.16 South zone load, chiller load and storage load; both charging and discharging are represented

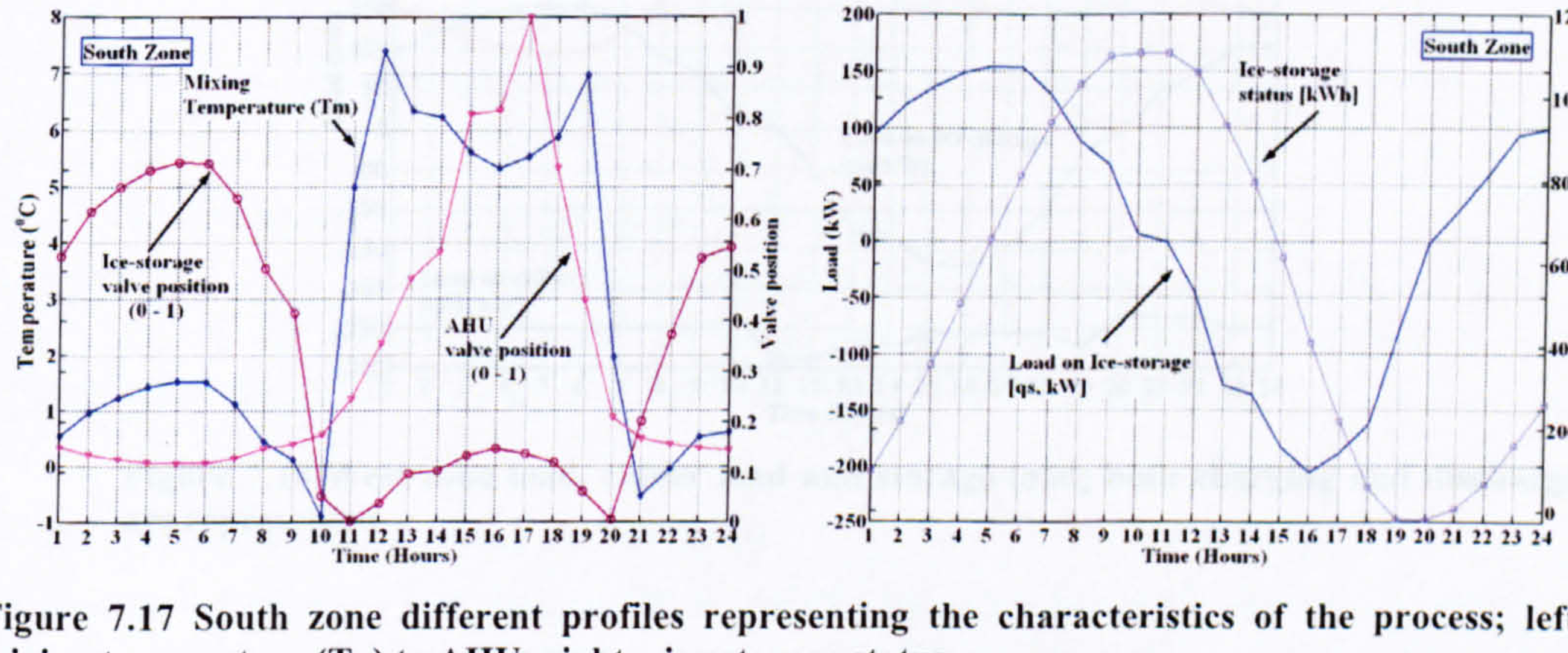

Figure 7.17 South zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

Table 7.4 South zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	154.5	-249.5	95	100	0.6	0.5	0.2
2	129.2	-249.5	120.3	220.3	1	0.6	0.1
3	112.7	-249.5	136.8	357	1.2	0.7	0.1
4	100.9	-249.5	148.6	505.6	1.4	0.7	0.1
5	95	-249.5	154.5	660.1	1.5	0.7	0.1
6	96	-249.5	153.5	813.6	1.5	0.7	0.1
7	120.4	-249.5	129.1	942.7	1.1	0.6	0.1
8	160.7	-249.5	88.8	1031.6	0.5	0.5	0.1
9	181.3	-249.5	68.2	1099.8	0.1	0.4	0.2
10	229	-235.5	6.5	1106.3	-0.9	0.1	0.2
11	283.5	-283.5	0	1106.3	5	0	0.2
12	332.2	-286.5	-45.7	1060.6	7.4	0	0.4
13	398.3	-271.5	-126.8	933.8	6.3	0.1	0.5
14	407.1	-271.5	-135.6	798.2	6.2	0.1	0.5
15	439.1	-256.5	-182.6	615.6	5.6	0.1	0.8
16	461.6	-256.5	-205.1	410.5	5.3	0.1	0.8
17	445	-256.5	-188.5	222	5.5	0.1	1
18	418.8	-256.5	-162.3	59.7	5.9	0.1	0.7
19	350.2	-271.5	-78.7	-19	7	0.1	0.4
20	264.4	-263	1.4	-20.4	2	0	0.2
21	207.4	-235.5	28.1	7.8	-0.5	0.2	0.2
22	176.2	-235.5	59.3	67	0	0.4	0.2
23	155.6	-249.5	93.9	161	0.5	0.5	0.1
24	150	-249.5	99.5	260.5	0.6	0.5	0.1

7.3.1.4 Performance of the West Zone

The west zone peak load occurred at 16.00 hours with a demand of 430 kW. The ice store was charged until 10.00 hours. The following hour is when the discharging begins. Out of the 1106 kWh of stored energy, 930 kWh is depleted and 176 kWh has remained.

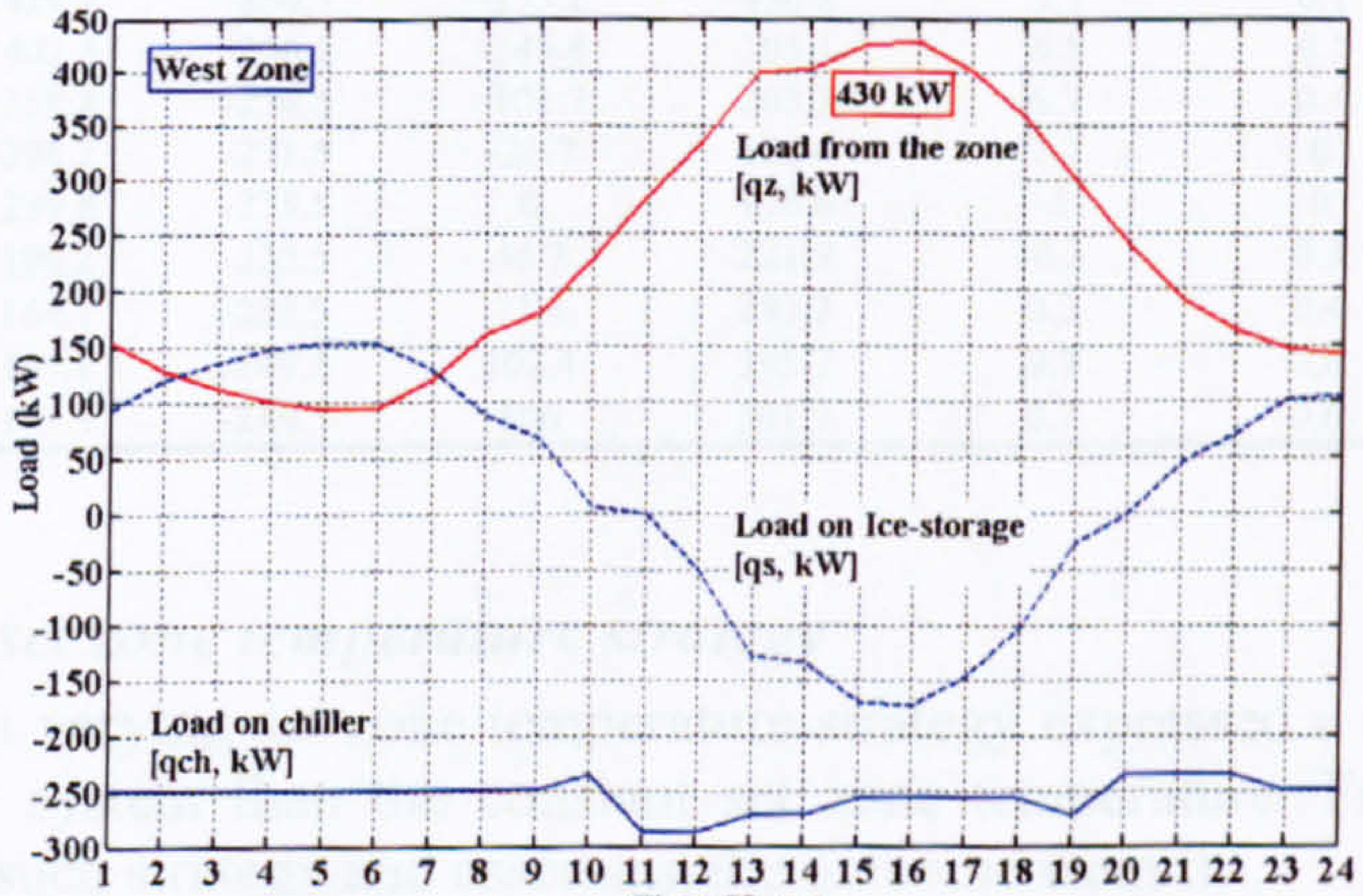

Figure 7.18 West zone load, chiller load and storage load; both charging and discharging are represented

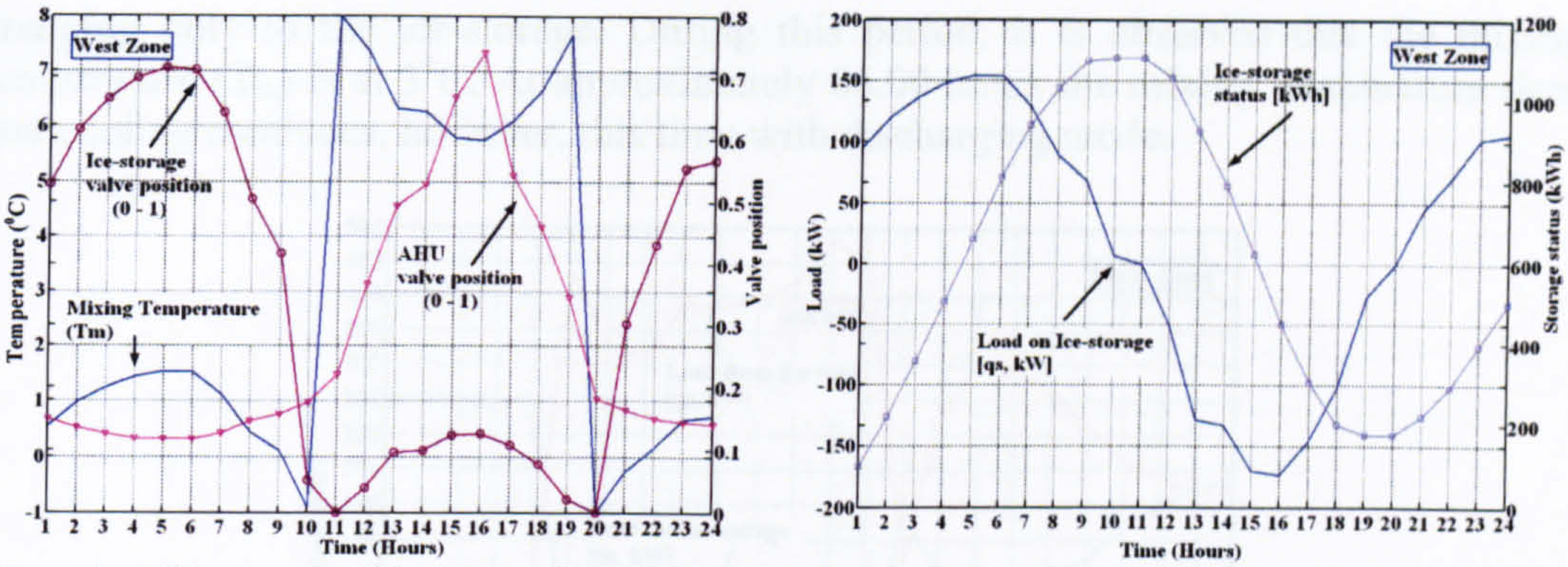

Figure 7.19 West zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

Table 7.5 West zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	154.5	-249.5	95	100	0.6	0.5	0.2
2	129.2	-249.5	120.3	220.3	1	0.6	0.1
3	112.7	-249.5	136.8	357	1.2	0.7	0.1
4	100.9	-249.5	148.6	505.6	1.4	0.7	0.1
5	95	-249.5	154.5	660.1	1.5	0.7	0.1
6	96	-249.5	153.5	813.6	1.5	0.7	0.1
7	120.4	-249.5	129.1	942.7	1.1	0.6	0.1
8	160.7	-249.5	88.8	1031.6	0.5	0.5	0.1
9	181.3	-249.5	68.2	1099.8	0.1	0.4	0.2
10	229	-235.5	6.5	1106.3	-0.9	0.1	0.2
11	286.6	-286.5	-0.1	1106.2	8	0	0.2
12	337	-286.5	-50.5	1055.7	7.3	0	0.4
13	400.2	-271.5	-128.7	927	6.3	0.1	0.5
14	404.6	-271.5	-133.1	793.9	6.3	0.1	0.5
15	426.4	-256.5	-169.9	624	5.8	0.1	0.7
16	429.7	-256.5	-173.2	450.8	5.7	0.1	0.7
17	402.3	-256.5	-145.8	305.1	6.1	0.1	0.5
18	358.2	-256.5	-101.7	203.3	6.7	0.1	0.5
19	298.2	-271.5	-26.7	176.6	7.7	0	0.3
20	239.8	-235.5	0	176.6	-1	0	0.2
21	190.2	-235.5	45.3	221.9	-0.3	0.3	0.2
22	164.1	-235.5	71.4	293.2	0.2	0.4	0.2
23	147.1	-249.5	102.4	395.7	0.7	0.6	0.1
24	143.5	-249.5	106	501.7	0.7	0.6	0.1

7.3.2 Varying set zone temperature strategy

The profiles for a varying set zone temperature strategy expressed a different dynamic behaviour of the system than the constant set zone temperature. From there, it was worth looking at such strategy and assessing the outcome from it.

7.3.2.1 Performance of the North Zone

In Figure 7.20 below, the load of the selected day has a value of 486 kW. Observation can be made on how the ice-storage is trying to utilise the spare capacity of the chiller during the early hours of the day. Because of the different temperature setup load from the zone is at zero, however, the chiller continues to operate at full capacity providing charging only to the ice-storage. During this period, it is observed that the mixing temperature (T_m) is at 3°C. At approximately 06.00 hours the mixing temperature rises and cooling continues, however, this time with discharging mode.

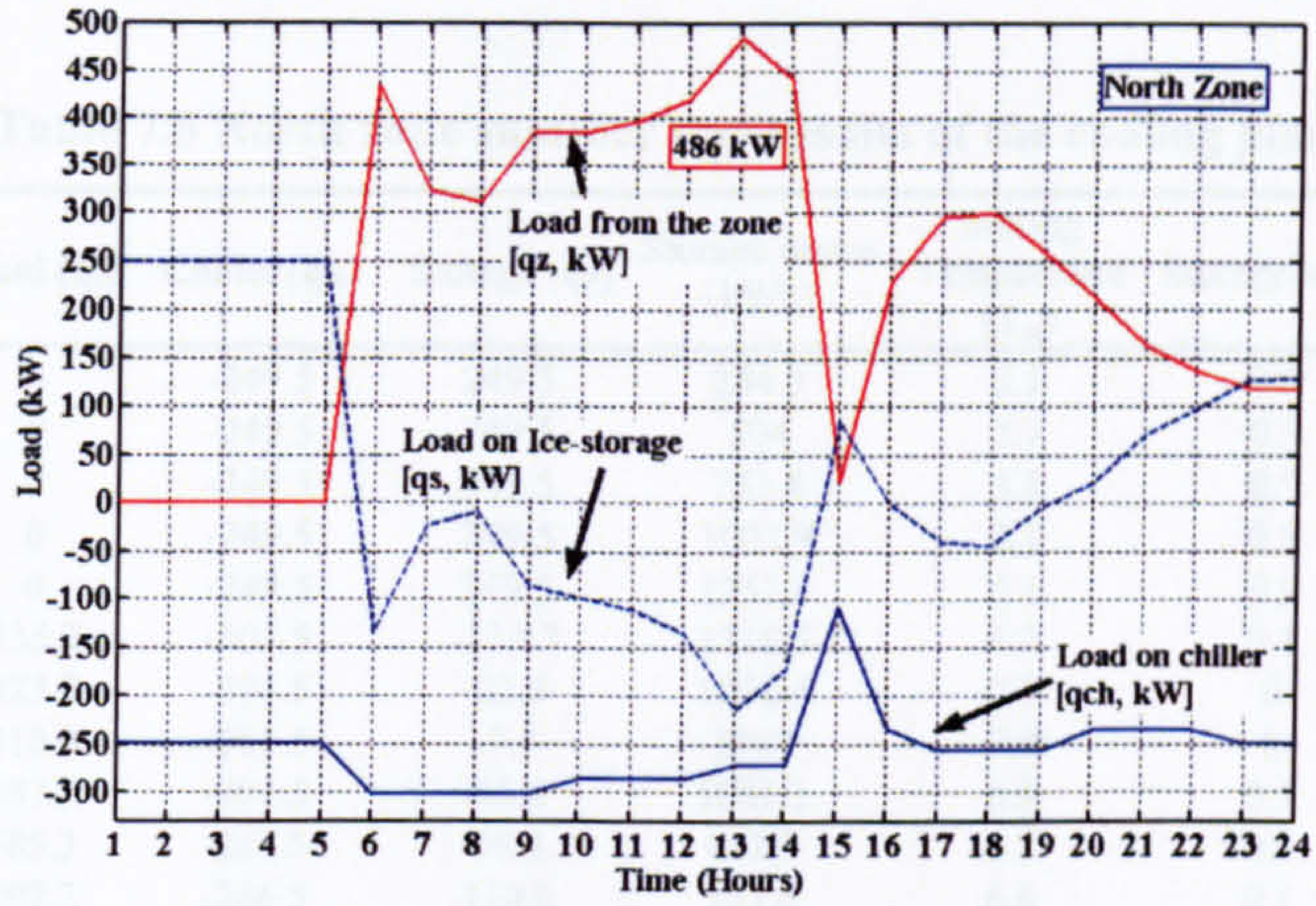

Figure 7.20 North zone load, chiller load and storage load; both charging and discharging are represented

Yet again, the status of the ice-storage gives a good indication of the process, Figure 7.21. The figure shows the ice build up in the tank starting from 12.00 midnight. The charging continues until 05.00 a.m. in the morning. At 06.00 a.m., the system switches to discharging as the demand rises beyond the capacity of the chiller. This is because the temperature set for the indoor is automatically switched from 28°C to 24°C. At that point, a sudden increase in the demand takes place. This is because requirement for cooling the building to a lower temperature is in place. This is illustrated in the three figures related to the north zone. Discharging stays in action until 19.00 hours and then the system switches back to cooling and charging again.

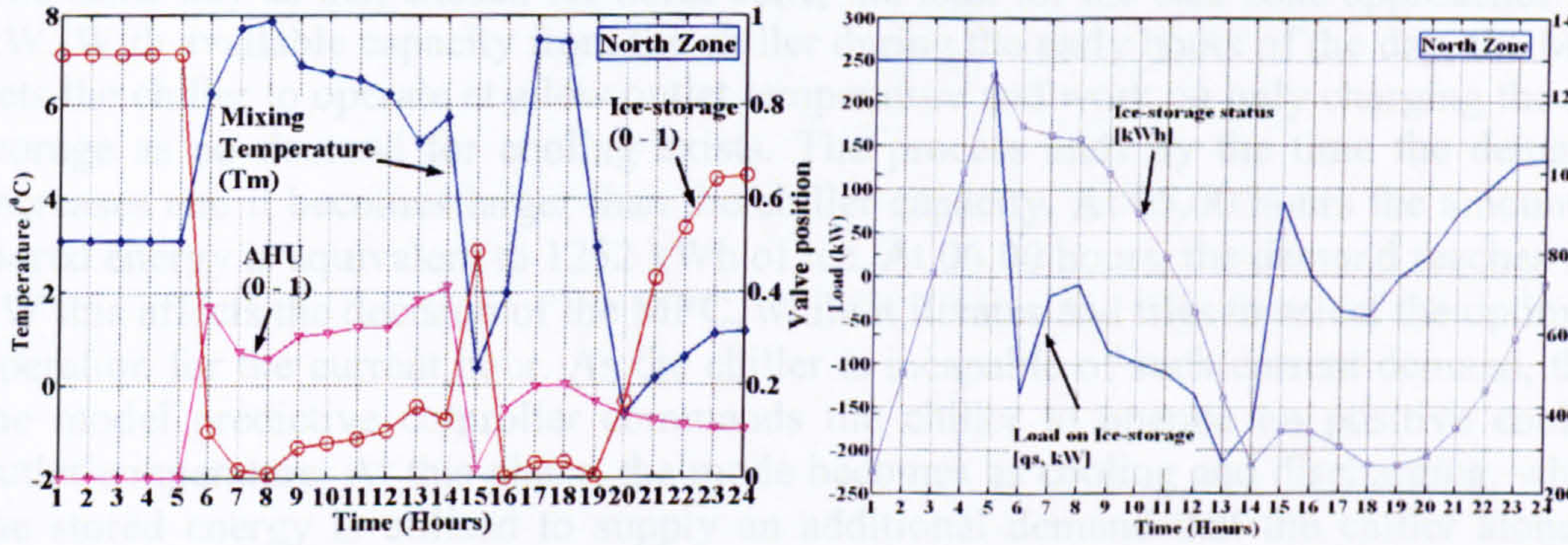

Figure 7.21 North zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

An hourly iteration process is conducted through the MPC in searching for the optimum operating conditions for the optimum strategy for operating the ice-storage unit. It is noticed that at 06.00 hours a big boost in the load occurs. This is when lighting, machines and other equipment are scheduled to operate. While this happens, the MPC switches the operating mode into discharge mode. This is because the load is higher than the chiller capacity. The effect of this process can be observed on the behaviour of the mixing temperature (T_m), the behaviour of both the ice-storage valve and the AHU valve can be noted, Figure 7.21.

Table 7.6 North zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	0	-249.5	249.5	254.5	3.1	0.9	0
2	0	-249.5	249.5	504	3.1	0.9	0
3	0	-249.5	249.5	753.4	3.1	0.9	0
4	0	-249.5	249.5	1002.9	3.1	0.9	0
5	0	-249.5	249.5	1252.4	3.1	0.9	0
6	435.2	-301.5	-133.7	1118.7	6.3	0.1	0.4
7	323.8	-301.5	-22.3	1096.4	7.7	0	0.3
8	310.9	-301.5	-9.4	1087	7.9	0	0.3
9	387.3	-301.5	-85.8	1001.2	6.9	0.1	0.3
10	385.3	-286.5	-98.8	902.4	6.7	0.1	0.3
11	397.3	-286.5	-110.8	791.6	6.6	0.1	0.3
12	421.2	-286.5	-134.7	656.9	6.2	0.1	0.3
13	485.7	-271.5	-214.2	442.7	5.2	0.2	0.4
14	442.9	-271.5	-171.4	271.3	5.8	0.1	0.4
15	22.6	-107.5	84.9	356.2	0.4	0.5	0
16	230.3	-233.5	0	356.2	2	0	0.1
17	296.4	-256.5	-39.9	316.3	7.5	0	0.2
18	301	-256.5	-44.5	271.8	7.4	0	0.2
19	259.7	-257.5	-2.2	269.6	3	0	0.2
20	213.3	-235.5	22.2	291.8	-0.6	0.2	0.1
21	164.3	-235.5	71.2	363.1	0.2	0.4	0.1
22	138.1	-235.5	97.4	460.5	0.6	0.5	0.1
23	120.8	-249.5	128.7	589.1	1.1	0.6	0.1
24	118.2	-249.5	131.3	720.4	1.2	0.7	0.1

7.3.2.2 Performance of the East Zone

The same day as that chosen for north zone, the load for the east zone approaches 383 kW. With available capacity from the chiller during the early hours of the day, the MPC sets the chiller to operate at a low outlet temperature and work on only charging the ice-storage as no demand for cooling exists. The process ends by the time the demands increases and it becomes larger than the chiller capacity. At 05.00 hours the amount of stored energy is equivalent to 1252 kWh of ice. At 06.00 hours, the demand reaches 358 kW this affects the decision of the MPC, while it iterates and tries to select the optimum operation for the current hour. As the chiller is incapable of such current demand, then the model predictive controller commands the chiller to operate on positive coolant outlet temperature. At this phase, the mode becomes as cooling and discharging, where the stored energy is utilised to supply an additional demand that the chiller alone is unable to provide.

Table 7.7 East zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	0	-249.5	249.5	254.5	3.1	0.9	0
2	0	-249.5	249.5	504	3.1	0.9	0
3	0	-249.5	249.5	753.4	3.1	0.9	0
4	0	-249.5	249.5	1002.9	3.1	0.9	0
5	0	-249.5	249.5	1252.4	3.1	0.9	0
6	437.3	-301.5	-135.8	1116.6	6.2	0.1	0.4
7	339.6	-301.5	-38.1	1078.6	7.5	0	0.3
8	351.6	-301.5	-50.1	1028.5	7.3	0	0.3
9	461.3	-301.5	-159.8	868.6	5.9	0.1	0.4
10	429.2	-286.5	-142.7	725.9	6.1	0.1	0.3
11	420.8	-286.5	-134.3	591.6	6.3	0.1	0.3
12	434.9	-286.5	-148.4	443.2	6.1	0.1	0.3
13	493.3	-271.5	-221.8	221.4	5.1	0.2	0.4
14	448.6	-271.5	-177.1	44.2	5.7	0.1	0.4
15	29.4	-107.5	78.1	122.4	0.3	0.5	0
16	236.6	-233.5	-3.1	119.2	2	0	0.1
17	307.5	-256.5	-51	68.2	7.3	0	0.2
18	317.8	-256.5	-61.3	6.9	7.2	0	0.2
19	278.5	-271.5	-7	-0.1	7.9	0	0.2
20	229.7	-235.5	5.8	5.7	-0.9	0	0.1
21	176.1	-235.5	59.4	65.1	0	0.4	0.1
22	146.6	-235.5	88.9	154	0.5	0.5	0.1
23	126.8	-249.5	122.7	276.7	1	0.6	0.1
24	122.8	-249.5	126.7	403.4	1.1	0.6	0.1

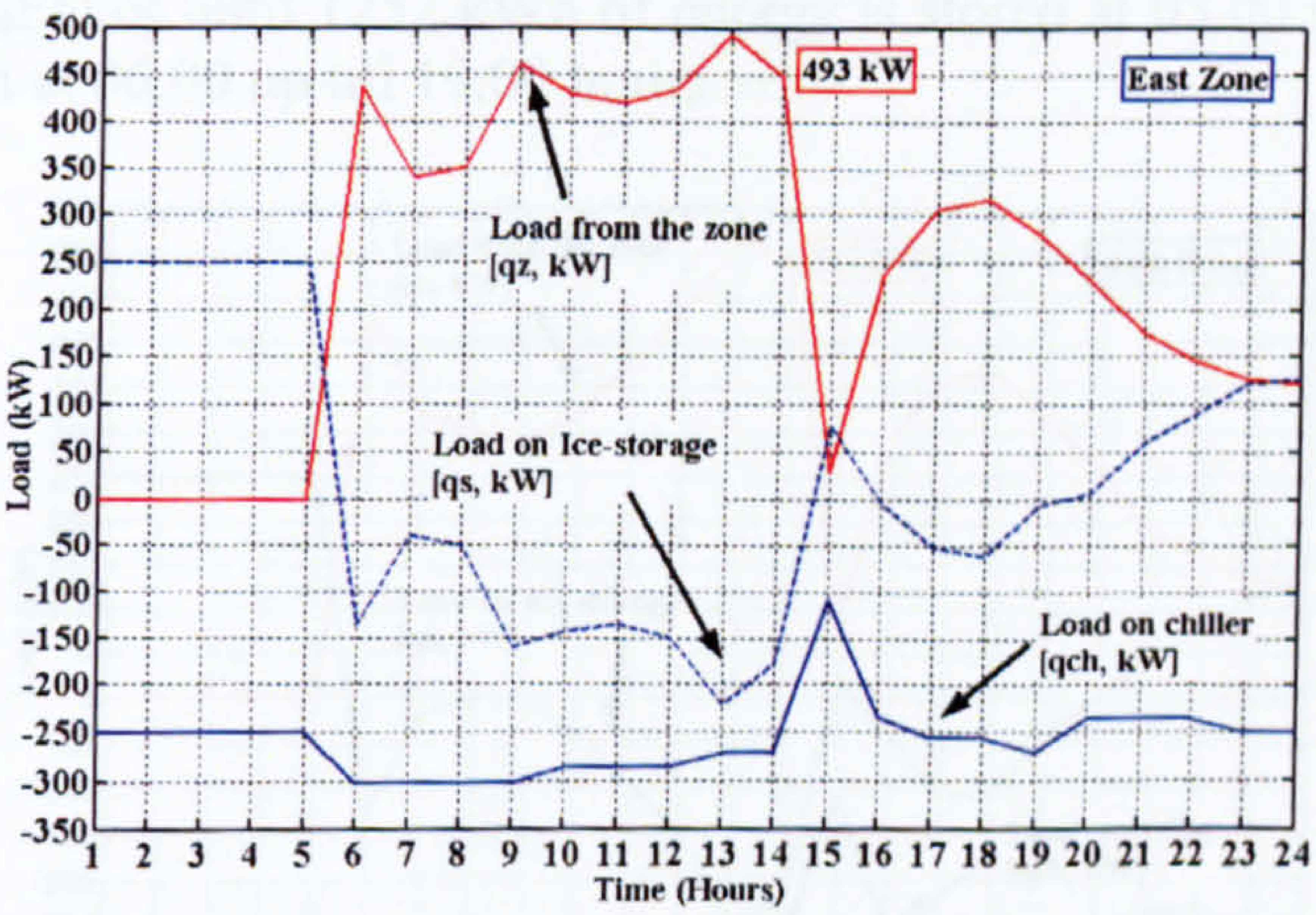

Figure 7.22 East zone load, chiller load and storage load; both charging and discharging are represented

Examining the mixing temperature (T_m) profile above, Figure 7.23, it is noticeable that during the charging mode the mixing temperature (T_m) has low values. At the time the system switches to cooling and discharging mode, the mixing temperature (T_m) rises and is trying to remain in the range between 5°C to 8°C. It is also evident that during the charging period that the ice-storage valve is mainly the one taking control of the process as it is nearly open up to 90% or more indicating that the coolant is going through the storage tank to charge and freeze its content of liquid water. With the cooling and discharging process starting, the valves switch positions and the valve for the AHU mainly takes control.

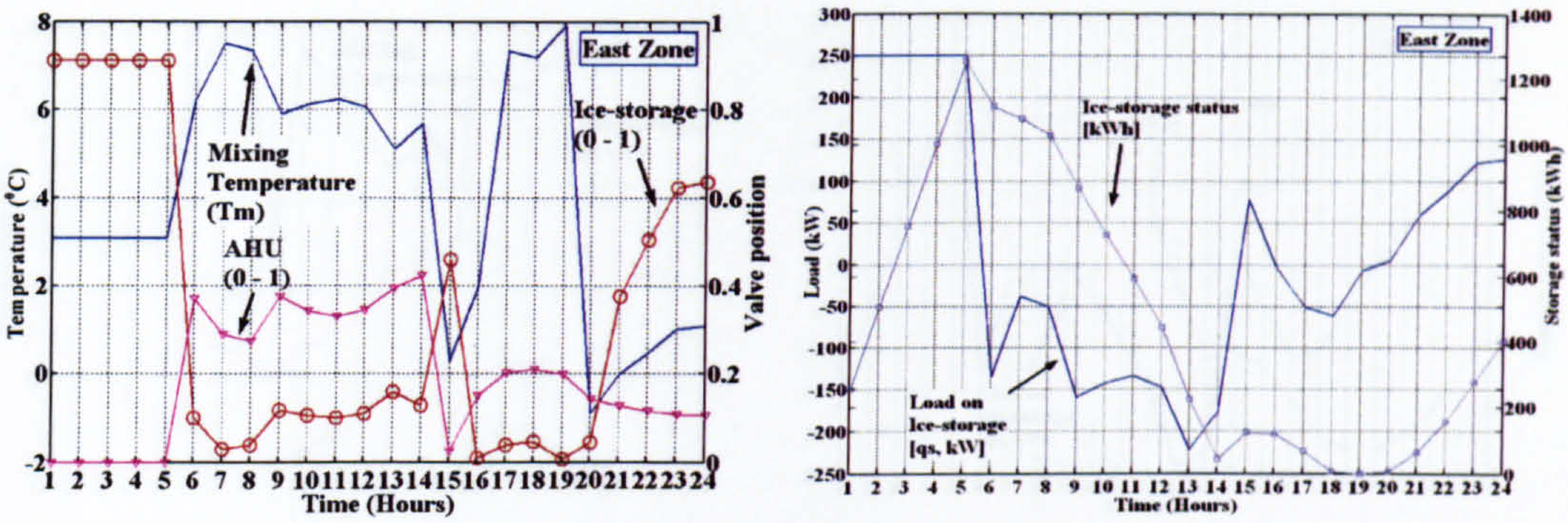

Figure 7.23 East zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

7.3.2.3 Performance of the South Zone

Looking at the representative graphs of the south zone, Figures 7.24 and 7.25, it can be observed that the same process keeps repeating for all the four zones. The peak load of the south zone occurs at 13.00 hours with the peak demand at 517 kW. Again, this is clearly the effect of its orientation. As the south zone faces the sun at mid-day period the effect of solar gain and the rise in ambient temperature is reflected by the zone having higher demand values than the north and east zones. Charging only starts at midnight and continues until 1252 kWh of energy is stored at 05.00 hours. Cooling and discharging begin at 06.00 up till 19.00 hours.

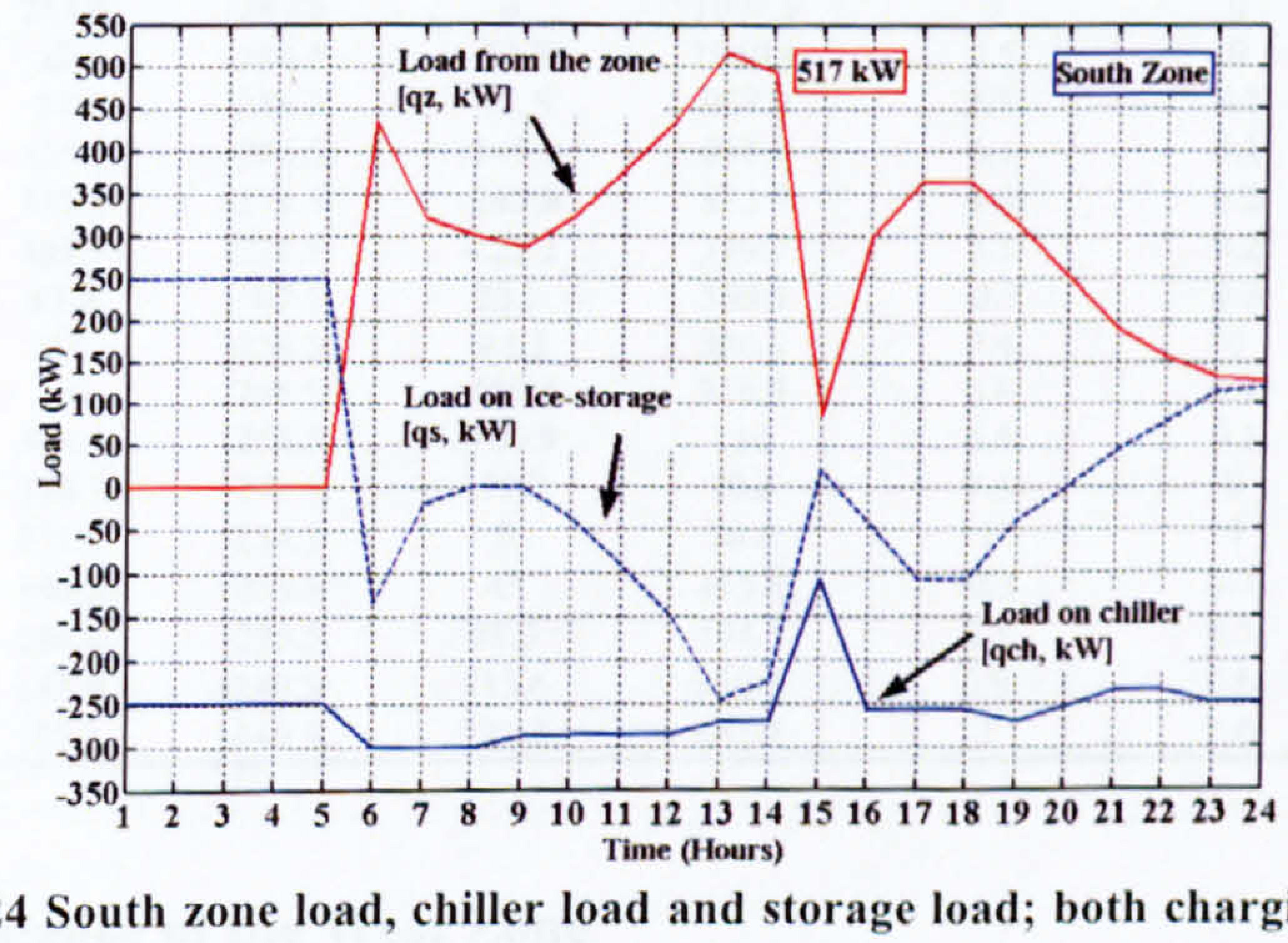

Figure 7.24 South zone load, chiller load and storage load; both charging and discharging are represented

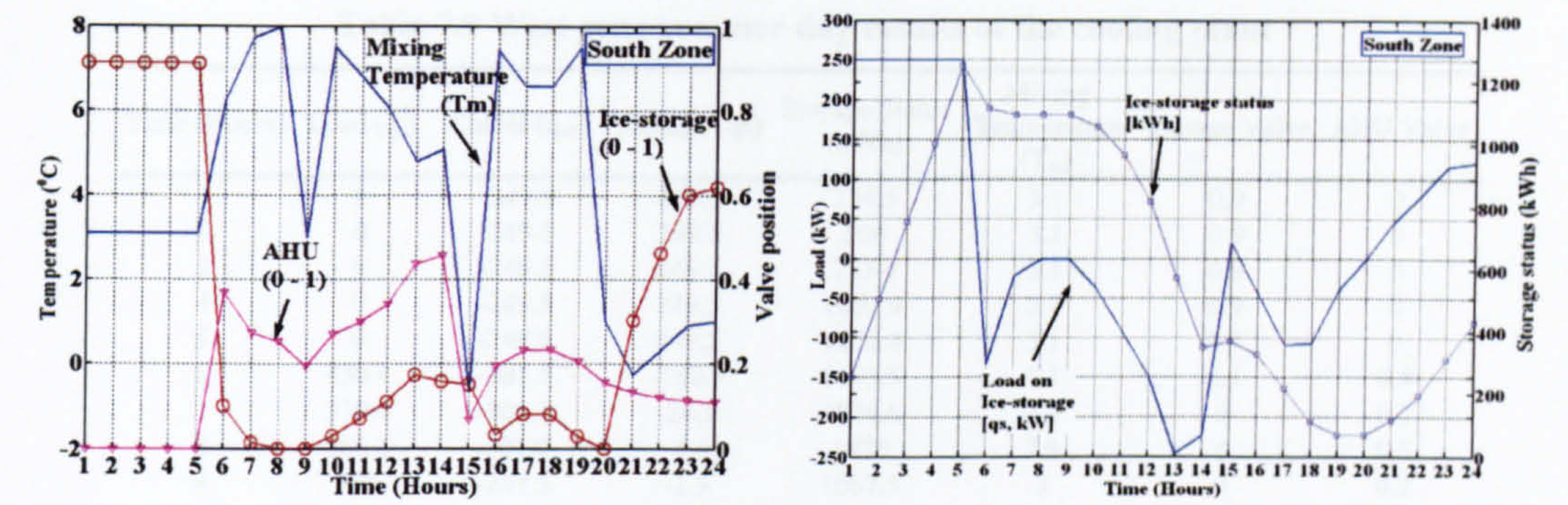

Figure 7.25 South zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

Table 7.8 South zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	0	-249.5	249.5	254.5	3.1	0.9	0
2	0	-249.5	249.5	504	3.1	0.9	0
3	0	-249.5	249.5	753.4	3.1	0.9	0
4	0	-249.5	249.5	1002.9	3.1	0.9	0
5	0	-249.5	249.5	1252.4	3.1	0.9	0
6	435.2	-301.5	-133.7	1118.7	6.3	0.1	0.4
7	322.2	-301.5	-20.7	1098	7.7	0	0.3
8	301.6	-301.5	-0.1	1097.9	8	0	0.3
9	287.4	-287.5	0	1097.9	3	0	0.2
10	324	-286.5	-37.5	1060.4	7.5	0	0.3
11	379	-286.5	-92.5	967.9	6.8	0.1	0.3
12	435.6	-286.5	-149.1	818.8	6.1	0.1	0.3
13	517.4	-271.5	-245.9	572.9	4.8	0.2	0.4
14	494.7	-271.5	-223.2	349.7	5.1	0.2	0.5
15	87.3	-107.5	20.2	369.9	-0.7	0.2	0.1
16	300	-256.5	-43.5	326.4	7.4	0	0.2
17	366	-256.5	-109.5	216.9	6.6	0.1	0.2
18	363.4	-256.5	-106.9	110	6.6	0.1	0.2
19	310.7	-271.5	-39.2	70.8	7.5	0	0.2
20	251.6	-254.5	0	70.8	1	0	0.2
21	190.5	-235.5	45	115.8	-0.3	0.3	0.1
22	156.8	-235.5	78.7	194.5	0.3	0.5	0.1
23	133.9	-249.5	115.6	310.1	0.9	0.6	0.1
24	128.2	-249.5	121.3	431.3	1	0.6	0.1

7.3.2.4 Performance of the West Zone

West zone peak occur also at 13.00 hours with a demand of 520 kW. Storage is charged until 05.00 hours. The following hour is when the discharging takes place. The same process takes place as occurred on the other zones.

Table 7.9 West zone summer day results of the cooling plant

Time (Hours)	Load (q_z)	Chiller (q_{ch})	Storage (qs)	Storage Status (kWh)	Mixing Temperature (T_m)	Storage Valve	AHU Valve
1	0	-249.5	249.5	254.5	3.1	0.9	0
2	0	-249.5	249.5	504	3.1	0.9	0
3	0	-249.5	249.5	753.4	3.1	0.9	0
4	0	-249.5	249.5	1002.9	3.1	0.9	0
5	0	-249.5	249.5	1252.4	3.1	0.9	0
6	450.4	-301.5	-148.9	1103.5	6.1	0.1	0.4
7	330.4	-301.5	-28.9	1074.6	7.6	0	0.3
8	306.1	-301.5	-4.6	1070	7.9	0	0.3
9	290	-287.5	-2.5	1067.5	3	0	0.2
10	325.8	-286.5	-39.3	1028.2	7.5	0	0.3
11	383	-286.5	-96.5	931.7	6.7	0.1	0.3
12	442.4	-286.5	-155.9	775.8	6	0.1	0.3
13	520.1	-271.5	-248.6	527.2	4.8	0.2	0.4
14	490.5	-271.5	-219	308.2	5.1	0.2	0.5
15	60.3	-107.5	47.2	355.4	-0.2	0.3	0.1
16	255.6	-255.5	-0.1	355.3	7	0	0.2
17	314.9	-256.5	-58.4	297	7.2	0	0.2
18	314	-256.5	-57.5	239.5	7.3	0	0.2
19	268.9	-268.5	-0.4	239.1	5	0	0.2
20	219.9	-235.5	15.6	254.7	-0.7	0.1	0.1
21	168.7	-235.5	66.8	321.5	0.1	0.4	0.1
22	141.2	-235.5	94.3	415.8	0.5	0.5	0.1
23	123	-249.5	126.5	542.3	1.1	0.6	0.1
24	119.9	-249.5	129.6	671.9	1.1	0.6	0.1

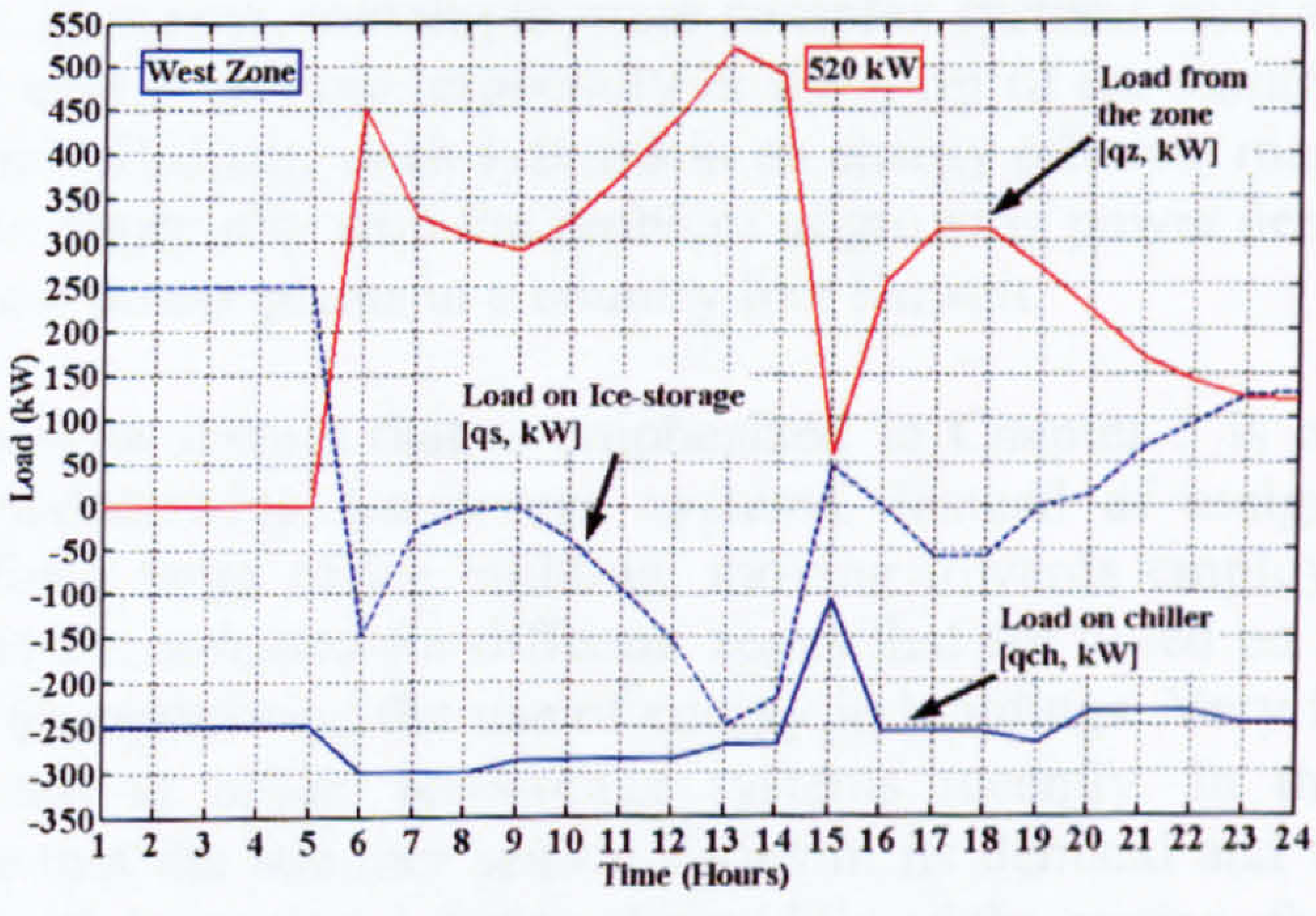

Figure 7.26 West zone load, chiller load and storage load; both charging and discharging are represented

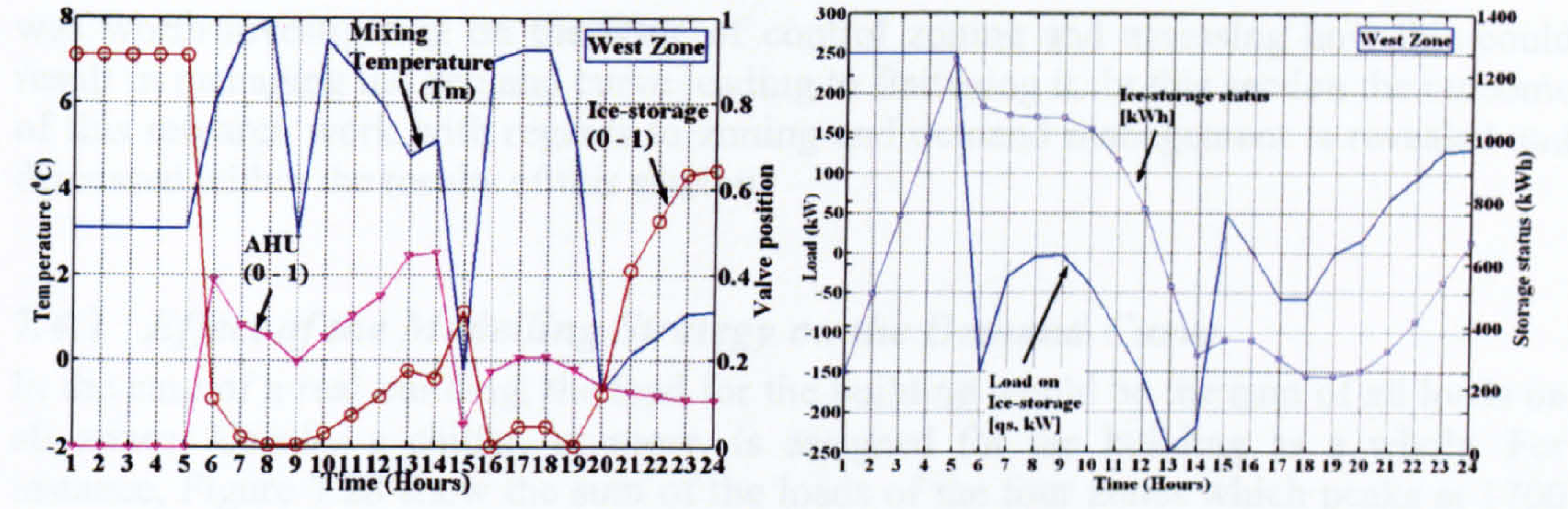

Figure 7.27 West zone different profiles representing the characteristics of the process; left - mixing temperature (T_m) to AHU; right – ice-storage status

7.4 On the Concept of Modularity

As it was stressed-on in earlier chapters, a principal part of this work is to investigate on the issues of demand-side Management (DSM) through a load shifting techniques as a way of load management. The intention here is to demonstrate that by treating each orientation as a separate zone that could improve, flatten, the demand curve.

The DSM concept has only been considered recently in Kuwait and adjacent countries in the region. Energy conservation measures were the first to be applied and utilised in the past few years. However, moving to more complex systems such as energy recovery units and thermal energy storage, especially in the form of ice-storage, are only recent arrivals to the region. Utilising such systems in an energy efficient manner is a matter of crucial importance. Especially with the problem of growing power demand and the need for constructing new power plants in a country like Kuwait.

The concept of control zoning that is emphasized in Chapter 5 is believed to be the means towards modularising ice-storage systems. Instead of assigning a large ice-storage system for a large office building, moving towards employing several units smaller in size that are assigned for different zones that are based on orientation would provide a ground for optimising the use of energy in buildings. Very few institutions in Kuwait have started to utilise ice-storage systems recently. In this thesis, it was highlighted earlier that the summer season varies in its demand and the season can be divided into the harsh heat period during the middle of the season, the hot temperature which also has a good proportion of the summer season and finally the warm period, which is just a month or a month and a half before the weather begins to get cooler for about the next two months. Mainly the utilised ice-storage systems are usually fully charged during the cooling season no matter which of these summer periods is being experienced.

Fully charging such systems during the mild season would result in wastage of energy. It is logical to state that, if energy is generated but not used then this could be considered as wasted energy. This brings to the conclusion that, a devise is known to be used to manage demands and optimise the use of energy is not used properly then this could mean energy is not being saved or its use is not being optimised. From here, it was worth investigating on the issue of control zoning and assessing how this could result in managing the demand curve leading to flattening it. In this section the outcome of this research work with regards to zoning and demand management is revealed and discussed within the results of this section.

7.4.1 Effect of the Modelling Strategy on the Demand Curve

In the case of a real building, the load for the building would be the sum of all loads on all zones. Usually a chiller, or more, is assigned for the building as a whole. For instance, Figure 7.28 show the sum of the loads of the four zones which peaks at 1700 kW, equivalent to 483 Tons at hour 16. On the other hand, the matlab-simulink accommodates a single zone cell that represents a simple building model. Upon that, each time a simulation was undertaken the model had to be assigned to a specific orientation. A comparative view of the load of the four zones is shown in Figure 7.29.

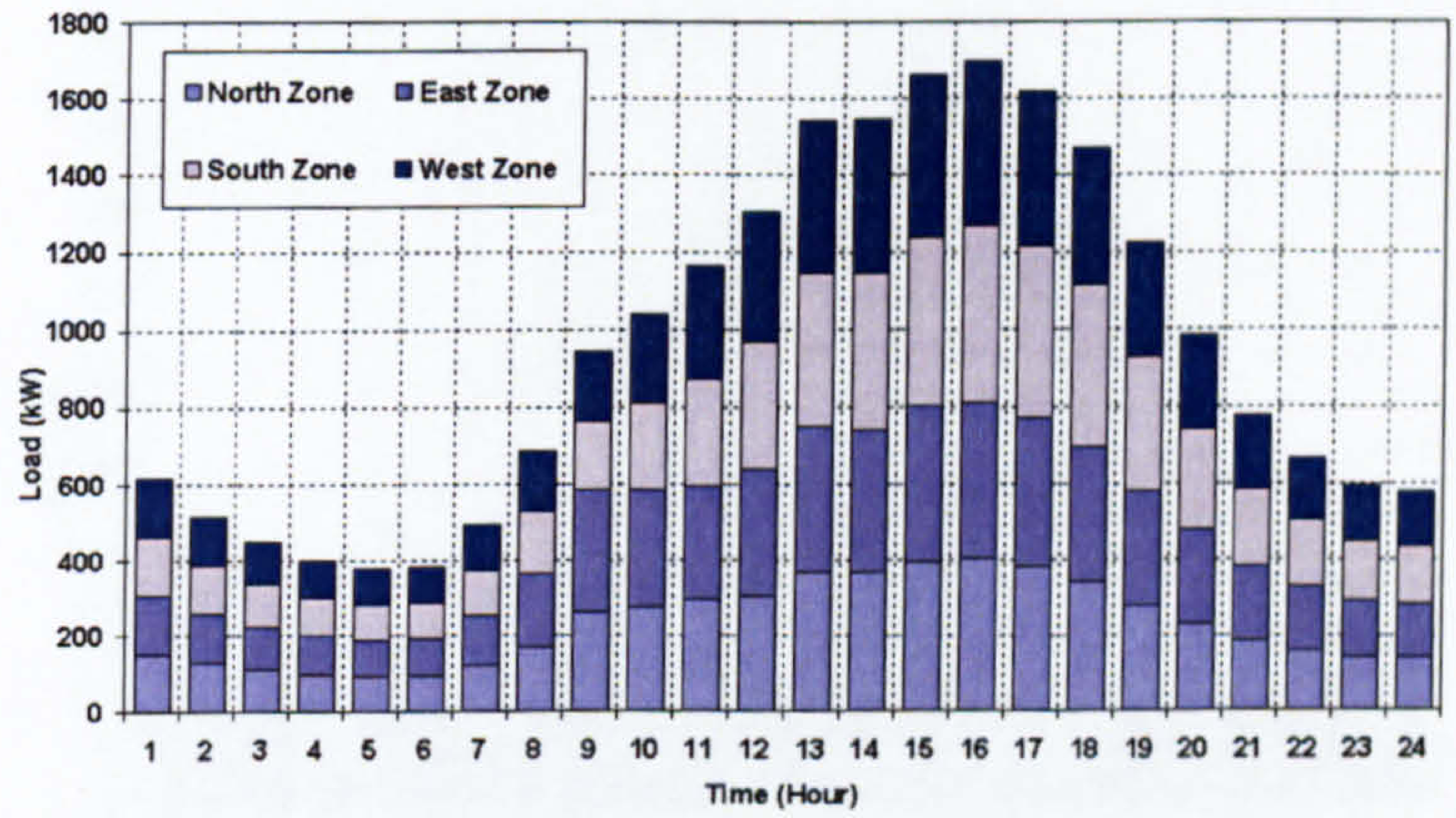

Figure 7.28 The sum of all four zones cooling load profile

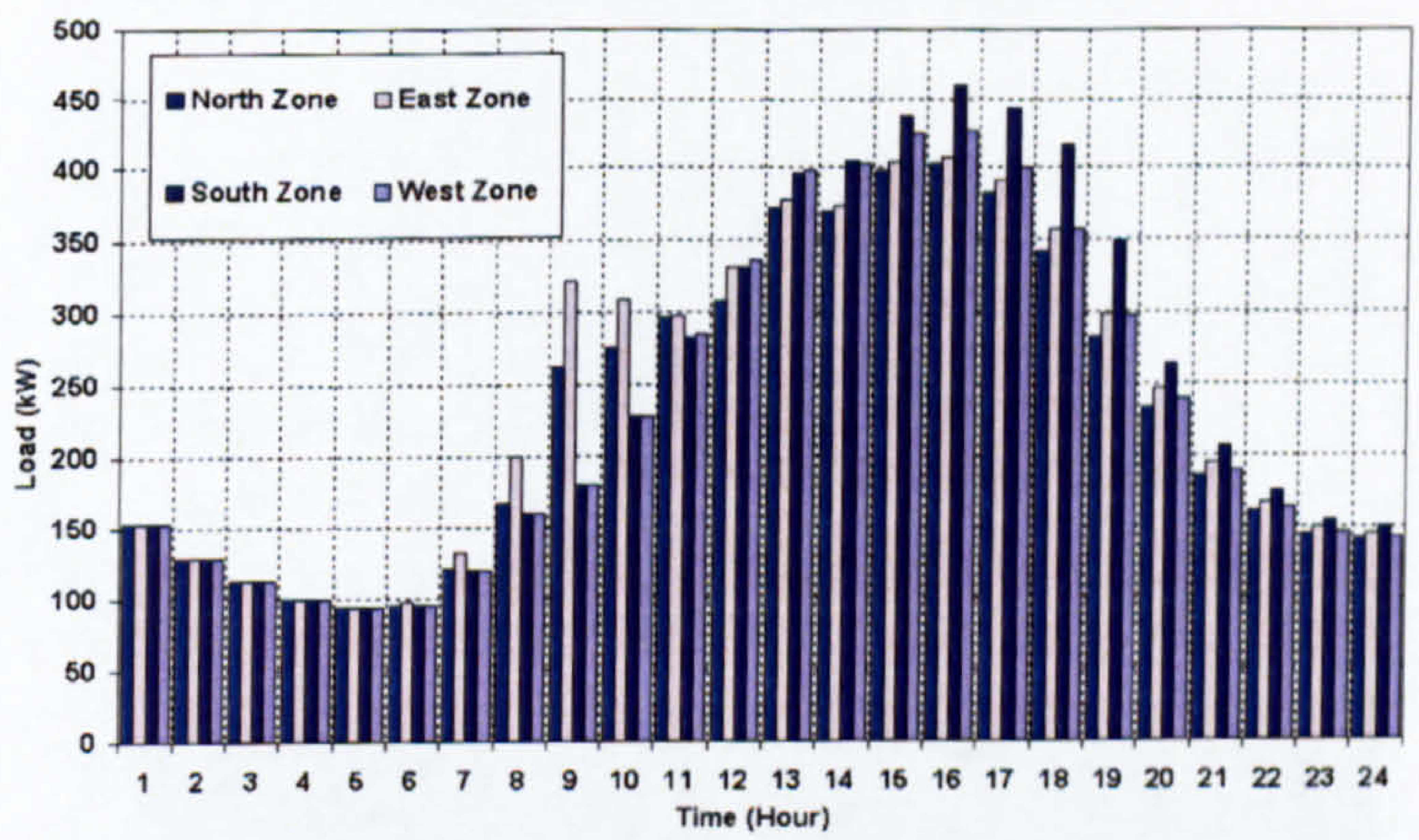

Figure 7.29 Comparative view of all four zones cooling load profiles

Figures 7.30 to 7.33 below represent the cooling load profiles of the north, east, south and west zones. As can be seen, during the early hours of the day, the demand curve is at its minimum levels. This is between the hours of 12.00 midnight and 07.00 in the morning. The demand curve then steeply increases between the hours of 09.00 and

16.00 hours. Different parameters play a role and when combined together, they provide the logic to explain the shape of the demand curve. As previously highlighted in Chapter 3, the high extremes in weather conditions carry the biggest share of the cause of the way the cooling demand behaves. Both the ambient temperature and solar radiation from the sun join together and are the main contributory factors producing the cooling demand. Their highest contribution is during the day time as Kuwait's climate is characterised by clear sky for most if not all of the summer season. This is obvious as during the evening hours the effect of both disappears as can be from the cooling demand profiles in figure 7.30 to 7.33 below. In addition, the model is characterised as an office building and different schedules for occupation and equipment usage that represent office practise are included. Part of the load can be credited to the scheduled lighting, machines and occupancy. These are scheduled to be valid between the hours of 07.00 and 15.00 hours. Afterwards, the demand starts decreasing as the effect of these parameters no longer apply.

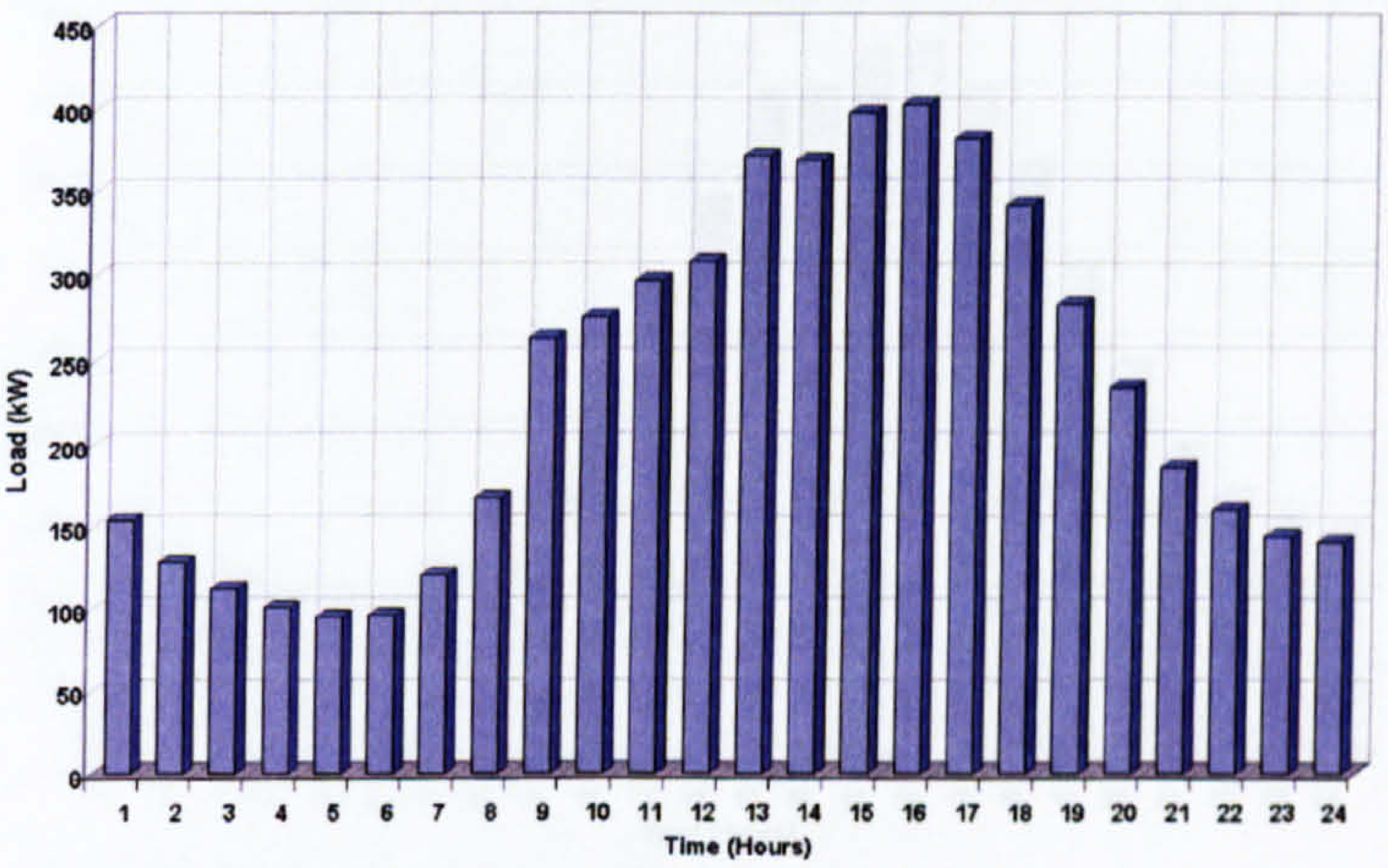

Figure 7.30 Cooling load profile for the North zone

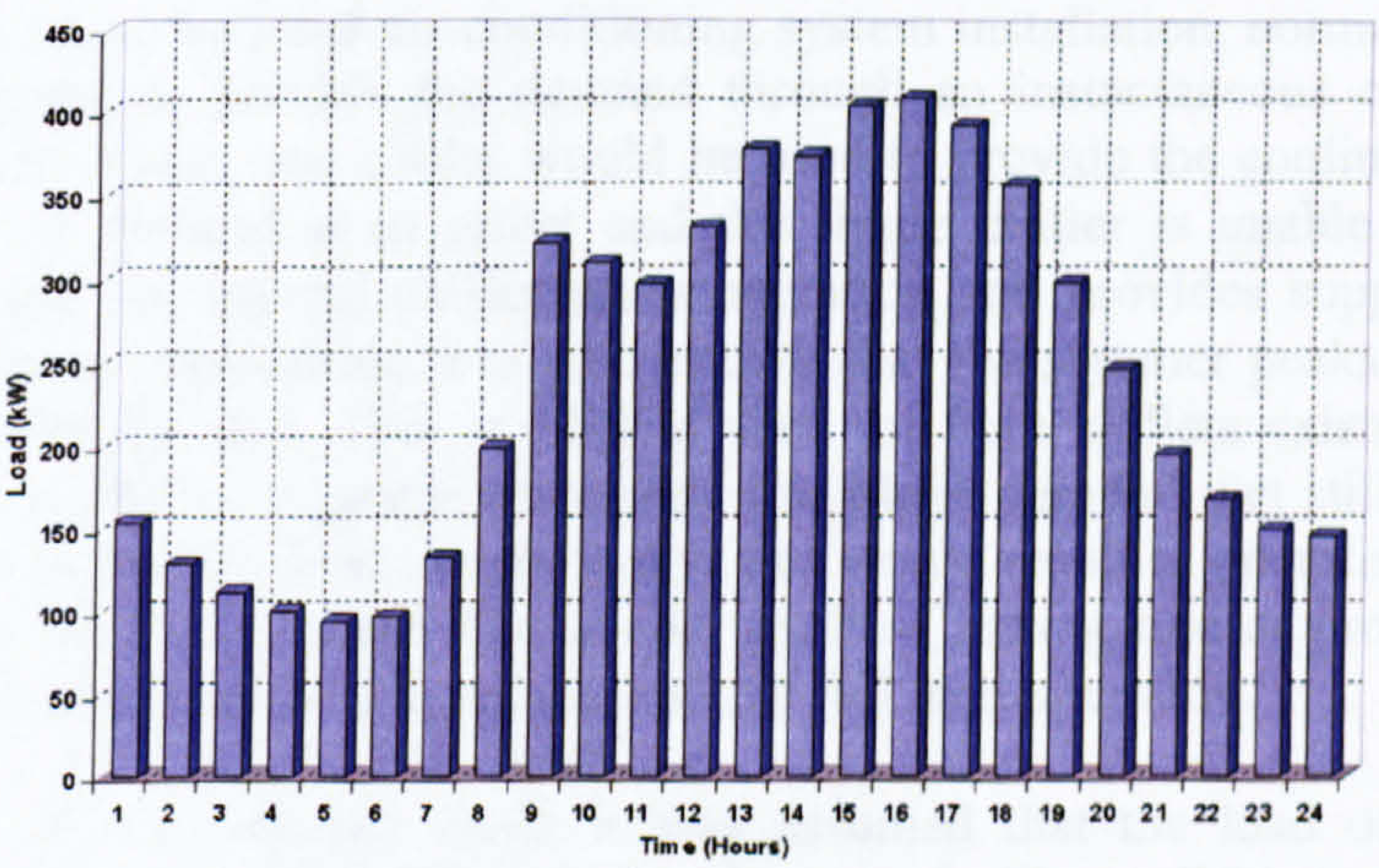

Figure 7.31 Cooling load profile for the East zone

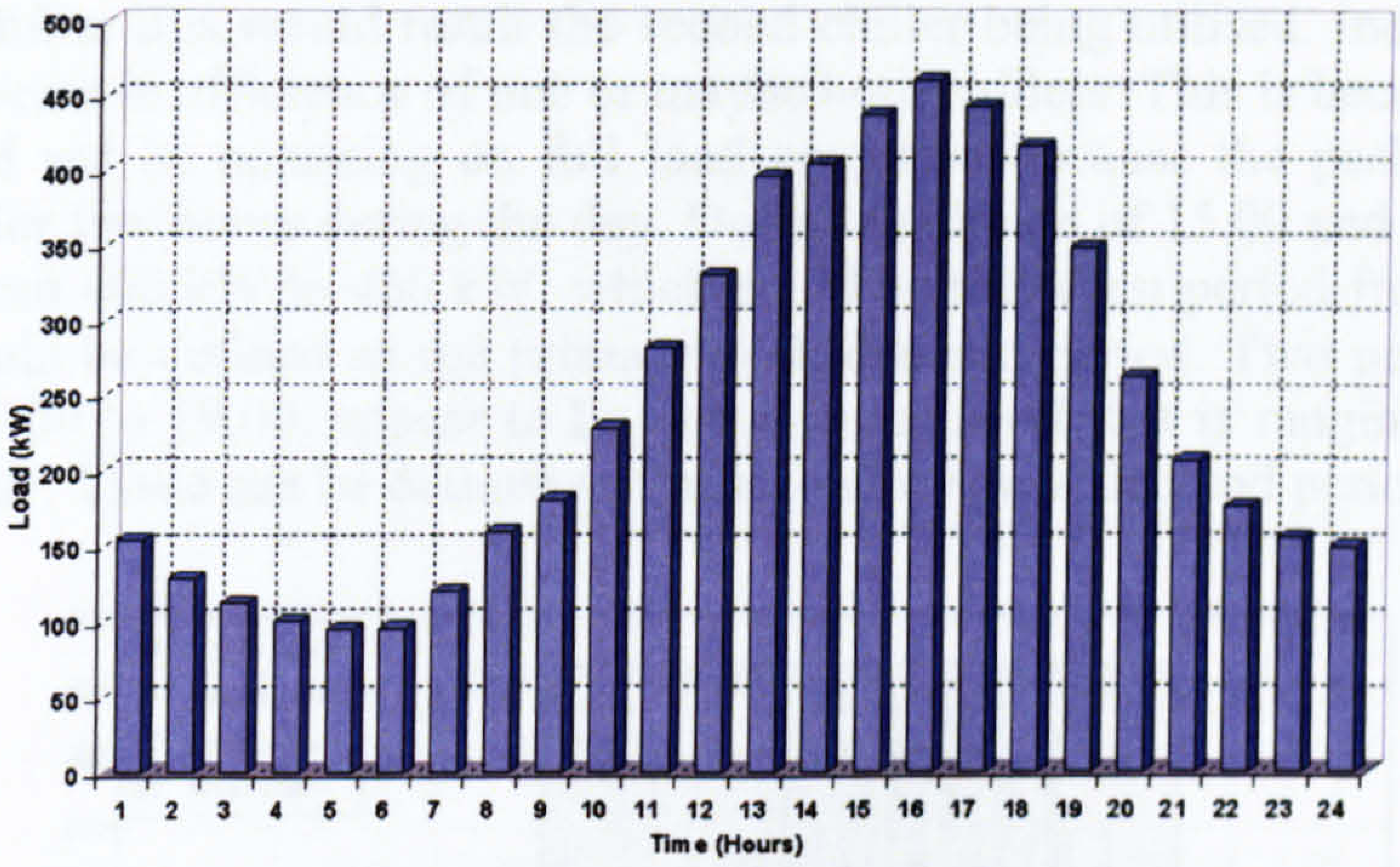

Figure 7.32 Cooling load profile for the South zone

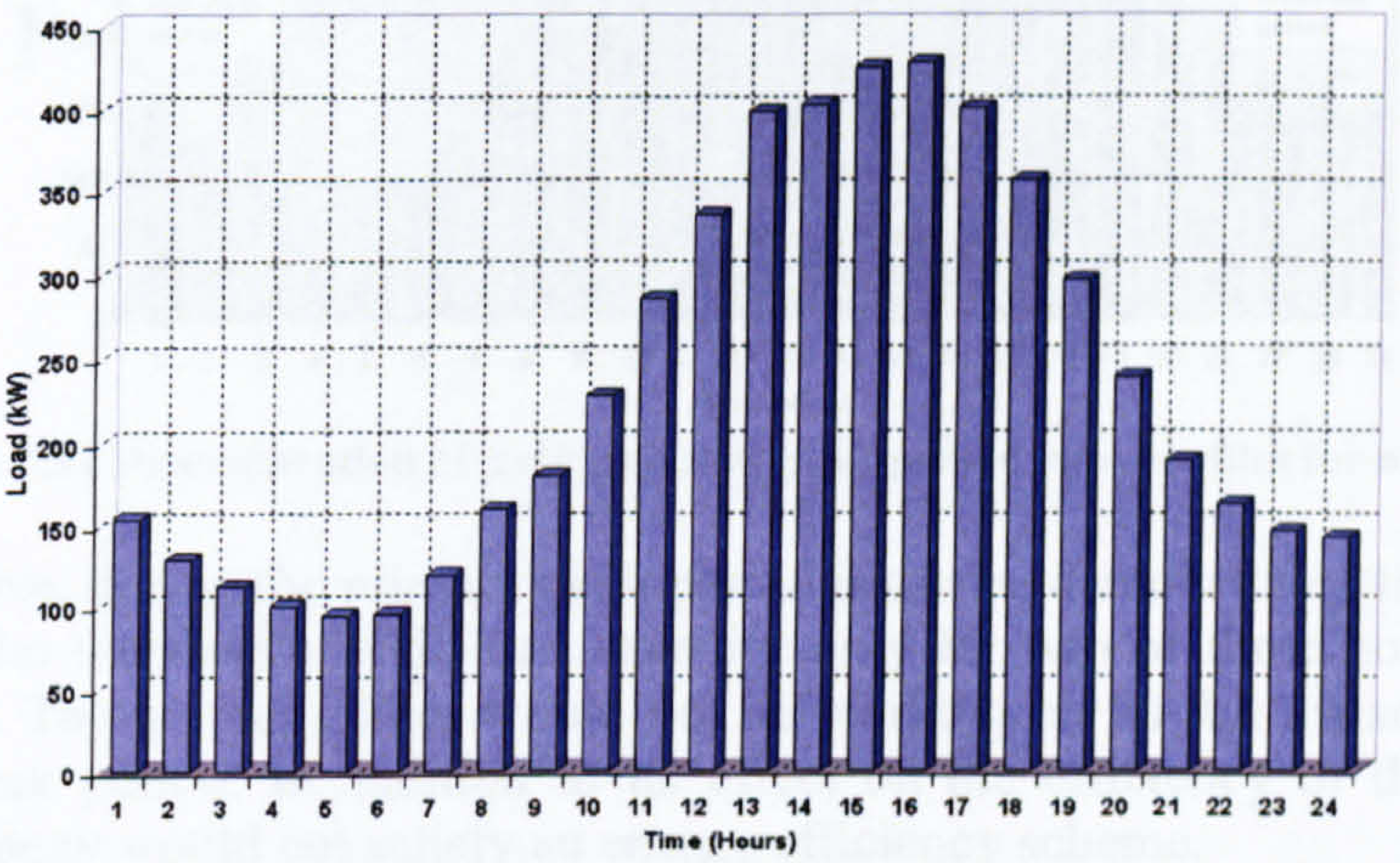

Figure 7.33 Cooling load profile for the South zone

In the case of a conventional air-conditioning system installation, normally two chillers will be employed to provide the demand through an instantaneous cooling process. During the early hours, one chiller would be used to provide the cooling. At later time when growth in demand is in effect and the single chiller is unable to provide the cooling required, the second chiller starts operation and provides support to the first chiller. In such an application, it is well known that the summer peaks only occur for few hours during the day. This is when a need for both chillers exists. During other times where one chiller is unable to provide the whole demand, yet still the demand is not equivalent to the full load operation and this would result in operating both chillers to provide the shortage. Indeed this would result of having one or probably both the chillers operating on part load operation and not full load operation.

For the sake of this research work, it was assumed that the load of each zone is accounted for as the building load. As can be seen in Figure 7.34 that the maximum load for a summer selected day occurs on the south zone with a peak load value of 460 kW. When two chillers with a capacity of 250 kW, equivalent to around 70 Tons, are installed then during the non-peak period, see Figure 7.34, only one chiller will be operating to provide the demand. Subsequently, when the demand exceeds the capacity of a single chiller this would result the second chiller being utilised. Indeed this would result in decrease in efficiency of one or maybe both chillers. This is because the second chiller would not be operating on full load operation because the peak demand only occurs only for few hours during the day. During the hours of 15.00 and 16.00, the load ranges between 400 kW to 460 kW, which could be the worst period from the demand view and could be defined as the primary peak demand period. Two periods, 11.00 to 13.00 and 17.00 to 19.00, appear to be at a demand level that is ranging between 300 kW to 400 kW. These can be defined as the secondary peak demand period.

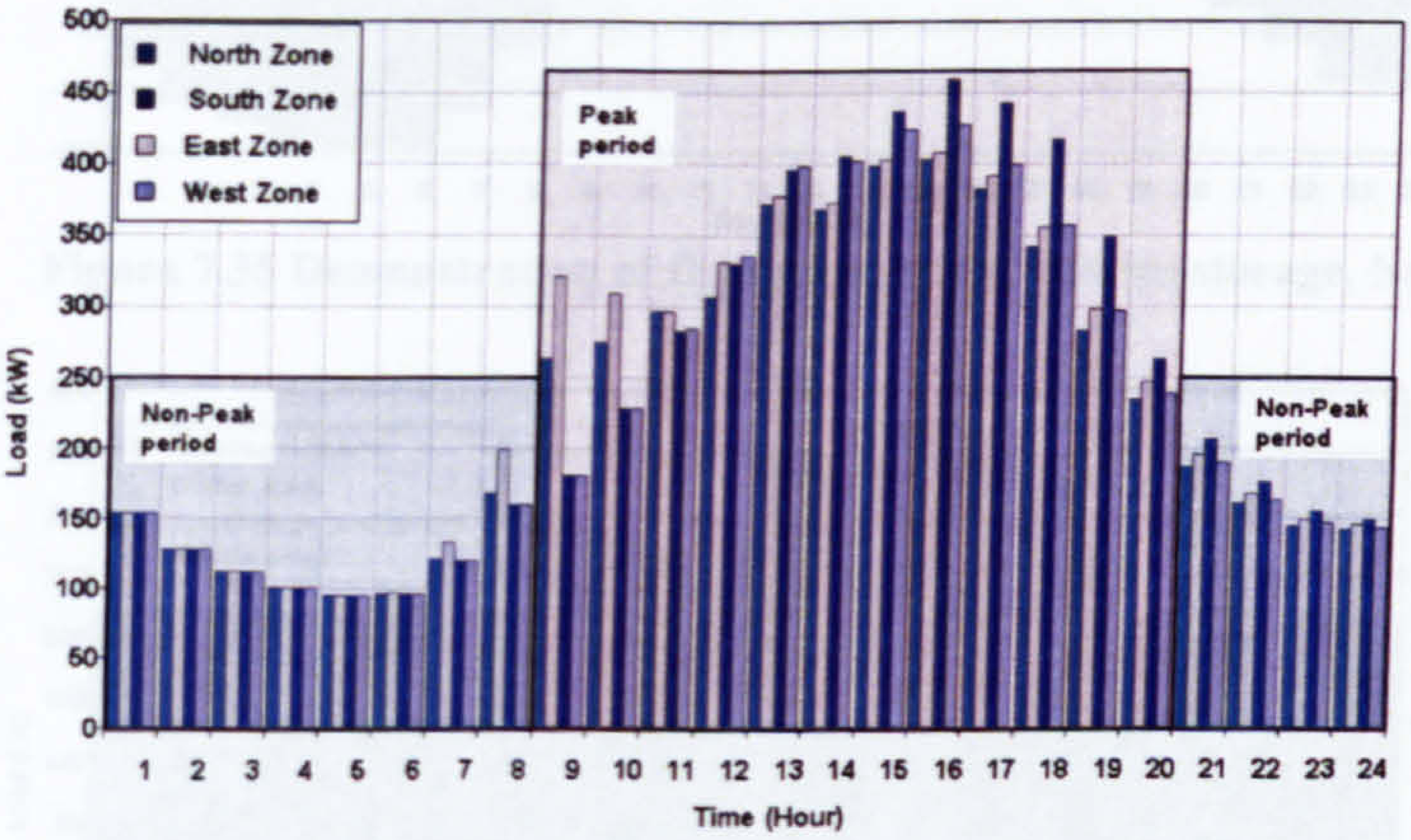

Figure 7.34 Demonstration of peak and non-peak period load profiles for all zones

From the above, during the primary peak period it can be demonstrated that the cooling plant would be working on full load capacity only for two or three hours during the example day. The second chiller would not be working on its full capacity during the secondary peak period. In addition to its effect on the efficiency of the chiller, this operating strategy would not satisfy an energy efficiency scheme.

If an ice-storage assisted air-conditioning system is employed, the system would not be operating with two chillers. The ice-storage system usually replaces the second chiller and carries its demand duties for the cooling season. Figures 7.35 to 7.38 below illustrate the performance of the Matlab model. For the same example day, it can be seen that the chiller is working on its full capacity for the period of the twenty four hours. This satisfies the condition of preventing the chiller from operating on part load operation and ensures that it operates on or near full load capacity for most of the summer period leading to a better efficiency of the chiller. During the mild period of the day, as the chiller is operating on full load and the demand is less than the output from the chiller, the extra capacity is being utilised and the ice-storage undergoes charging process. During the peak period where the increase in the demand starts building up, the chiller continues providing the demand as long as its capacity is sufficient to supply the demand. Once the demand goes higher than the capacity of the chiller, then the ice-storage undergoes discharging process to supplement the shortage in the capacity and top it up from the stored energy.

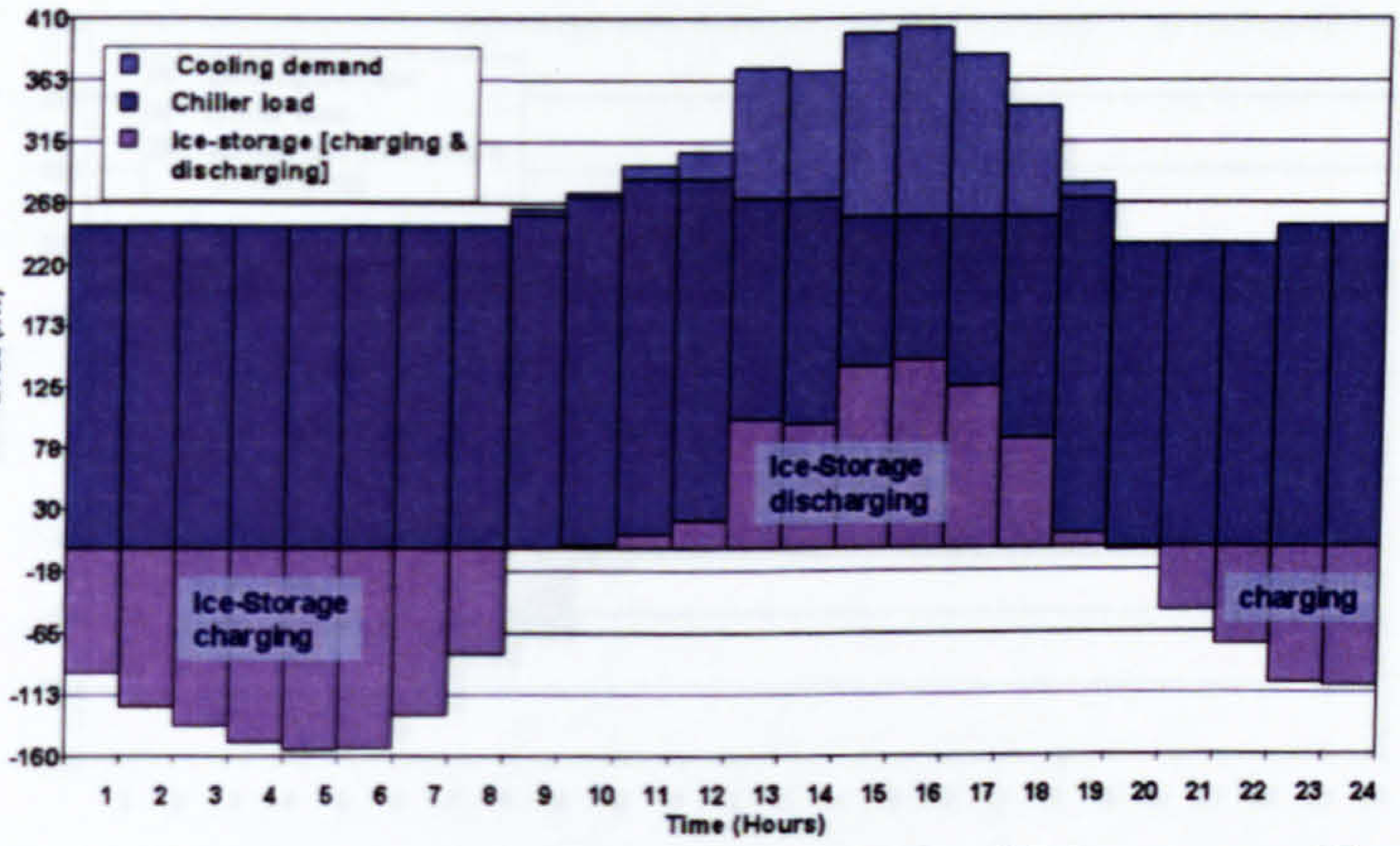

Figure 7.35 Demonstration of the system loads with ice-storage, North zone

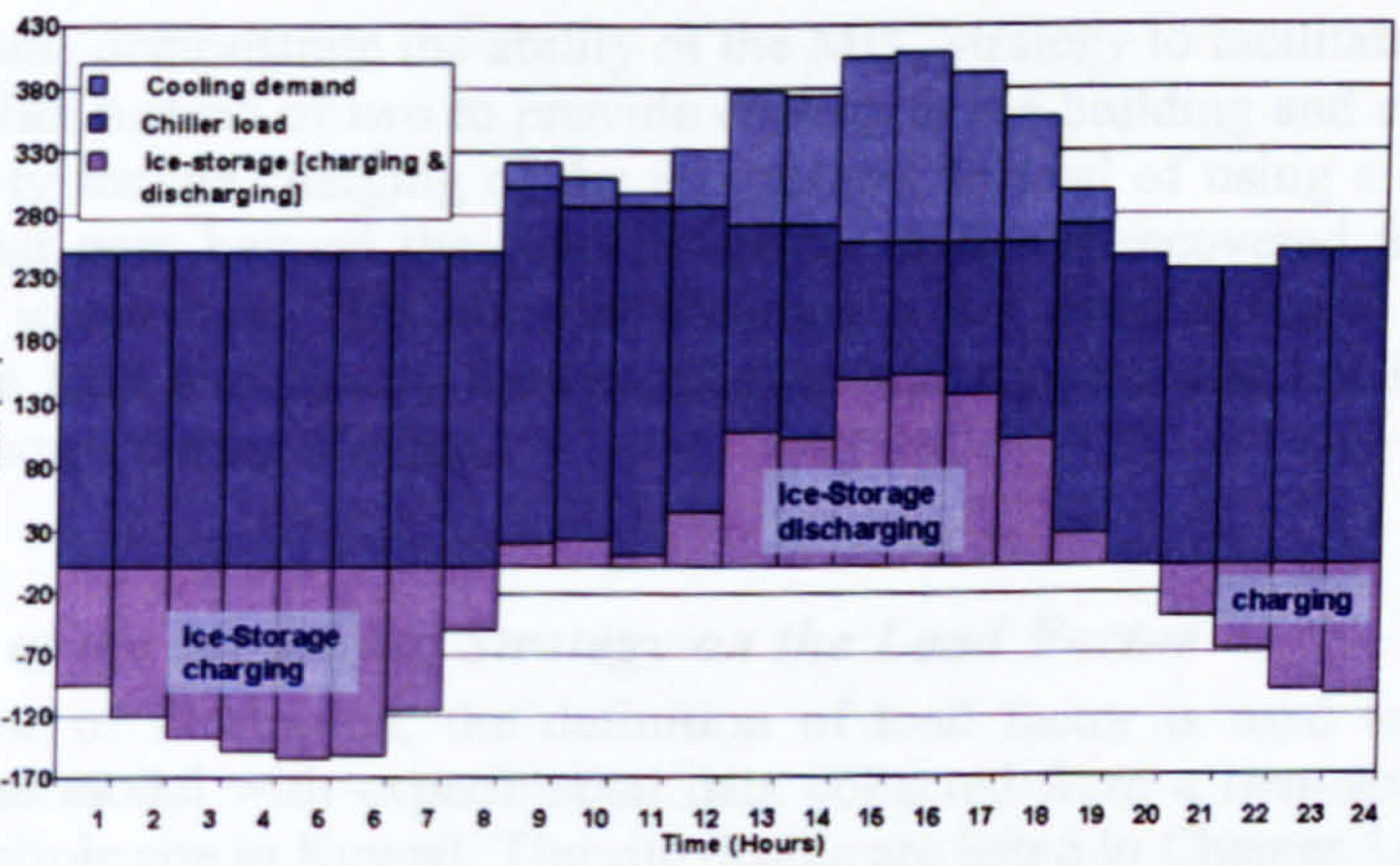

Figure 7.36 Demonstration of the system loads with ice-storage, East zone

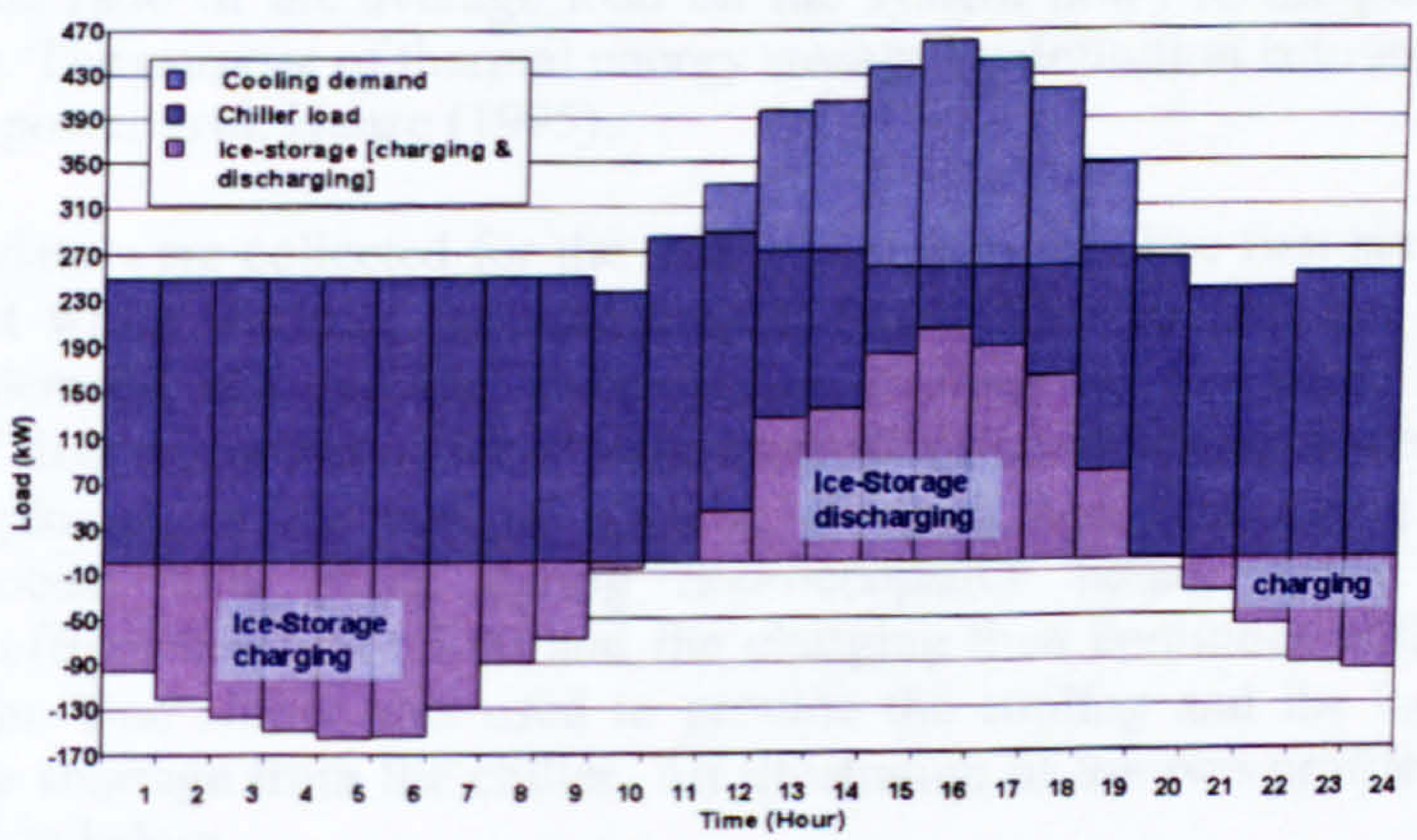

Figure 7.37 Demonstration of the system loads with ice-storage, South zone

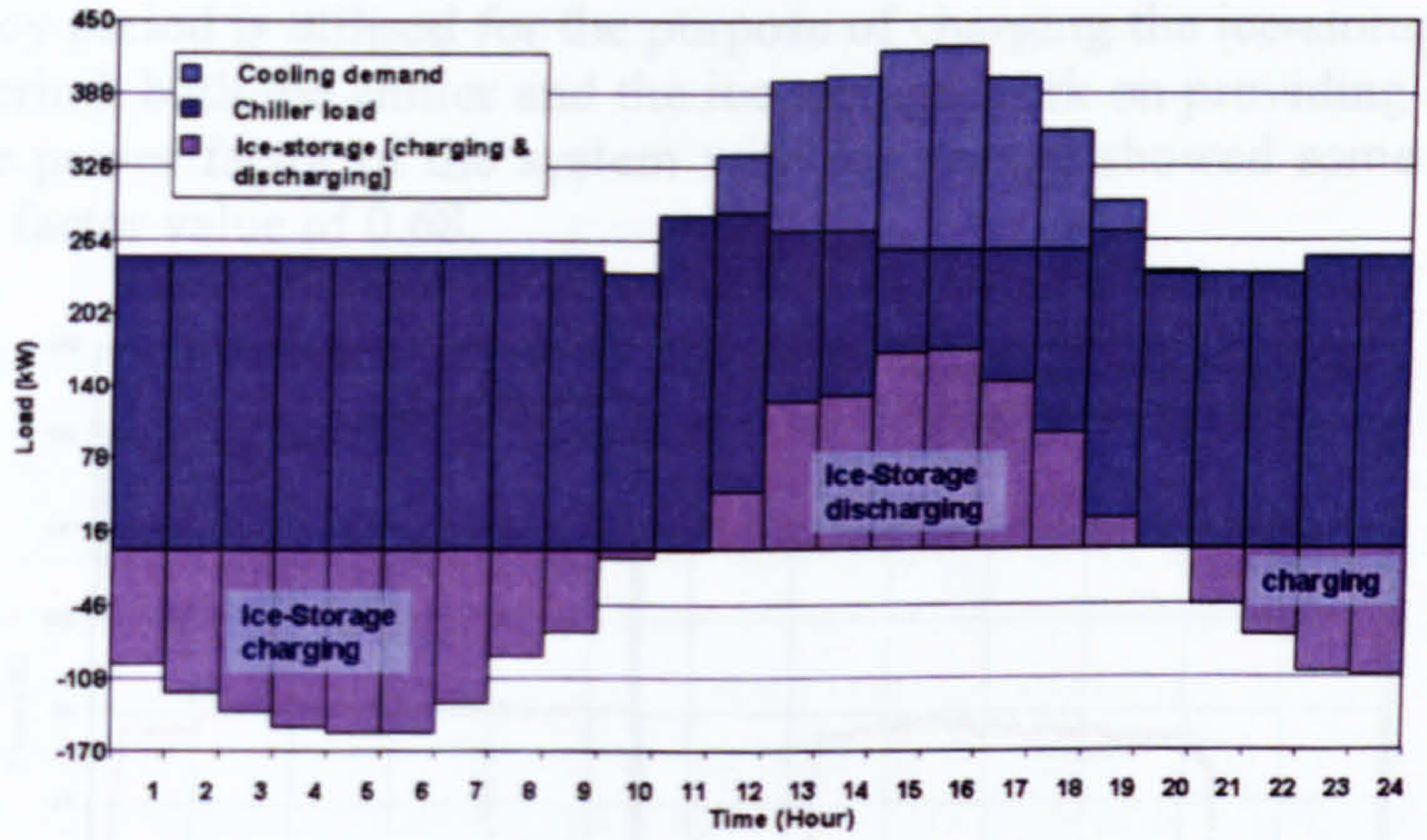

Figure 7.38 Demonstration of the system loads with ice-storage, West zone

The above results demonstrate the ability of the MPC strategy to facilitate the utilisation of a single chiller instead of two to provide cooling to the building and assign the spare cooling capacity for the charging of the ice-storage. Instead of using a second chiller, the demand that goes beyond the capacity of the chiller is recovered from the stored energy in the ice-storage. This allowed attaining a flat demand curve as a result of distributing the load over nearly the twenty-four hours period and not limiting it to a period of few hours during the day.

7.4.2 Effect of the Modelling Strategy on the Load Factor

For the purpose of illustration, the definition of load factor is used to compare the results from the model with experimental data collected from a two-story speech and audio therapy clinic site in Kuwait. The site details are listed in Chapter 3, under section 3.3.1.1. Load factor with reference to power utilities and building services application is defined as the ratio of the average load on the system (kW) to the peak load on the system (kW). The purpose of thermal energy storage by definition is to increase the load factor of the power grid, Henze (1995).

Two sets of data were collected for the sake of comparison. The first set represents the cooling plant while working on conventional basis. Two chillers are being used to supply the demand and provide instantaneous cooling for the clinic building. The second set of data represents an ice-storage assisted air-conditioning system. One chiller is being employed for the task of cooling, charging and discharging process. The charging process took place during non-occupancy hours, which for Kuwaiti government offices begin at 15.00 and the charging then continues until 01.00 hours after midnight. One chiller was used to provide the cooling and the ice-storage was supplying the shortage from the chiller. An illustration of the two profiles is presented in the Figure 7.39 below.

For a period of twenty-four hours, the conventional system had a load factor value of 0.4. As can be seen from Figure 7.39, the system is being used between the hours of 04.00 and 14.00. The system is then switched off until the next day. On the other hand, the ice-storage assisted HVAC system is used during two of periods during the day. The non-occupancy period is utilised for the purpose of charging the ice-storage. During the occupancy period, both the chiller and the ice-storage work on providing cooling to the building. The power factor of the system with ice-storage showed some improvement with a power factor value of 0.68.

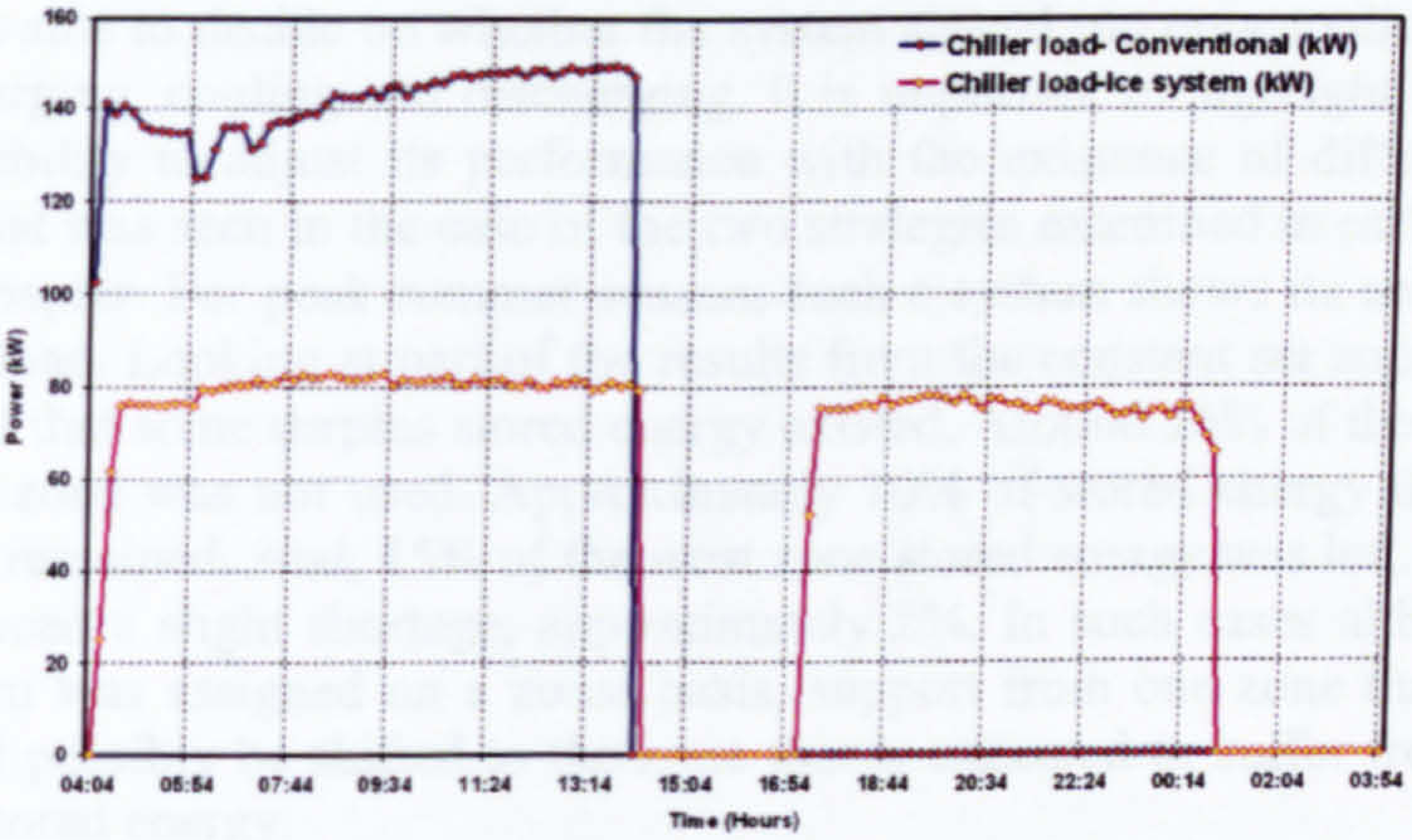

Figure 7.39 Experimental data collected from clinic

With regards to the Matlab model, testing the power factor was on the basis of orientated zones and also with all of the building zones combined together. The power factor for the individual zones and in total in addition to the power factor for the clinic are presented in Table 7.10.

Table 7.10 Load factor for the Matlab model and the clinic building

Zone	Matlab Model					Clinic Building	
	North Zone	East Zone	South Zone	West Zone	Combined zones	Conventional System	Ice-Storage System
Load Factor	0.894	0.859	0.891	0.887	0.894	0.396	0.687

Comparing the experimental data for both the conventional HVAC system and the ice-storage assisted HVAC system, it is obvious that the latter did achieve some enhancement in the power factor by 29%. From the presented results above, it appeared that the Matlab model with the MPC optimisation control strategy is achieving a power factor close to one. An average power factor of 0.882 was achieved by such a strategy. This implemented an improvement in the power factor of nearly 20% when compared to the actual ice-storage assisted HVAC system operation from the clinic and nearly 49% when compared with the conventional HVAC system from the clinic.

7.5 Conclusions

As "summer" conditions in Kuwait extend to a period of nearly eight months every year, the need for a system that is able to provide cooling through making use of the cooler periods during the day to produce and store cooling and utilise it at the severe or harsh period that triggers high peaks in demand is evident. Through exploring and discussing the results above, it is apparent that the model that has been developed is capable of performing several tasks. For the purpose of optimising the cooling production process, the model was examined and presented its ability to provide prediction upon the input parameters that have effects on the output of the cooling plant system model.

The model is able to decide on whether the system should run on a cooling, cooling and charging, charging, cooling and discharging. It is important to highlight that the model has got the ability to adjust its performance with the existence of different operation strategies. That was seen in the case of the two strategies examined in earlier sections of the current chapter. For peak summer season, such a system shows its ability to predict the next day load. Looking at part of the results from the constant set zone temperature, it was noticed that some surplus stored energy existed. Around 26% of the stored energy for the north zone was not used. Approximately 10% of stored energy that belongs to the east zone remained. And, 15% of the west zone stored energy was left. However, the south zone faced a slight shortage, approximately 2%. In such cases although the ice-storage system was assigned on a zonal basis, support from one zone that has surplus cooling could possibly be shifted to the zone that is expected to suffer from a shortage in available stored energy.

The summer season can have its peaks, where very hot days or months exist. Those are generally the months of June, July, and August in a country like Kuwait. Milder but still considered hot days come during times of the year adjacent to this 3 month period, where for example part of April and the whole of May and September represent such months. Even in October and some days of November could be accounted as belonging to such days. During the harsh summer months it would be possible to operate the chiller at its maximum output as there will always be a need for cooling with high demands so the need for ice-storage exists. However during milder periods, there will exist some days where cooling only is needed and a chiller would be able to supply the demand by itself. During such periods the need for energy to be storage would be unnecessary. Moreover, the days that fall between the days of harsh conditions and the days of warm conditions would require some usage of chillers and ice-storage combined. In such cases the need for storing only the amount of predicted demand from the ice-storage is due. An addition is needed for the model to evaluate the predicted status of the ice-storage, and then provide comparison between the amount of stored energy and the amount consumed. Then to judge the exact amount of energy that should be stored and limit the needed energy to be stored to that quantity.

Testing the model with the two set temperature strategies showed different behaviours and affected positively the amount of the demand for similar zones with different strategies. The variable set zone temperature showed a reduction in the cooling demand and consumption. As regards to electricity generation, thermal energy storage is known to conserve energy at the source of generation. The findings in this chapter agrees with what has been stated by McCannon (1995) when he defined thermal energy storage as a "source energy conservation", When added to site energy savings of storage, the net total reduction in fuel use and emission from thermal energy storage can be considerable.

Indeed the above profiles satisfy one of the main objectives of this research work. That is coming with a DSM control strategy that is not only successful in meeting the demand of an office building, but also utilises a strategy that provides the capabilities to utilise the optimum installed cooling capacity and not the maximum cooling capacity. Instead of satisfying the needs for cooling during a summer day with an extra installed capacity that will only be needed for few hours during the day, the MPC strategy employed with the ice-storage assisted HVAC model succeeded in changing the characteristic of the demand curve from a wavy profile with a peak in the middle of the afternoon into a nearly flattened profile. The result of such a strategy for the building operator is the saving of the cost of purchasing another chiller that would only be utilised for a short period of time and at low efficiency. For Kuwait at the national level cutting in the cost of investing in new power plants and extending the periods between such requirements can be considered enormous savings from economic viewpoint. Furthermore, this would help Kuwait and similar countries to conserve both their energy and financial resources and to protect the environment.

An additional objective of this work was to introduce the concept of modularity of ice-storage systems. This has been satisfied through assigning ice-storage to zones with specific orientations. The point behind this was that the ice-storage duty would satisfy the needs of a specific zone based on the orientation for that zone and that this would lead to the reduction of the size of the storage unit from one large unit of large capacity to a number of units with smaller capacities dealt with on zonal basis. In addition, adopting the concept of model predictive control and providing a model that is able to take the current condition of the real system and predict the future horizon of the system is considered as an advantage with regards to the modularity issue. Predicting the next day load and being able to have the model's feedback of what will be the predicted chiller share of the demand provides the basis for the facility to only charge the ice-storage systems assigned for zones based on orientation.

As an optimisation strategy, the MPC ice-storage assisted HVAC system model achieved a promising improvement in the value of the load factor. When compared to experimental data collected from a clinic building, the developed model with MPC achieved nearly 50% improvement in the value of the load factor.

In this chapter, the ice-storage system was tested through a model predictive control strategy with the effect of the different zones reflected and emphasized. In order to predict the future behaviour of a process, a model of how the process behaves must be available. The initial simulink model was used to provide the base to the model predictive control strategy implemented. This base model is capable of showing the dependence of the cooling load on the different variables such as weather conditions, occupancy, lighting, occupancy and non-occupancy periods.

"The significant problems we face cannot be solved at the same level of thinking we were at when we created them." (Albert Einstein.)

Chapter 8

Conclusions & Future Work

8.1 Conclusions

Energy shortage, environmental degradation and rapid growth in the cost of electrical power production form together the force towards shifting from Supply Side Management (SSM) towards the introduction and development of Demand Side Management (DSM) strategies. Strategies integrated from DSM can be utilised to tackle the high energy consumption rates of building services in offices and commercial buildings. If these systems are optimally controlled this can produce reductions in the rates of energy consumption. Adopting optimal control in office buildings provides opportunities for optimising energy efficiency through improved operation and control strategies and through integrated building services systems.

Kuwait is one of many countries in the world that rely heavily on air-conditioning systems for the cooling of buildings. Air conditioning installations absorb 60 to 70 percent of the primary energy consumed nationally. A need for the continual construction of new power plants is required to satisfy the continual growth of this demand. Consequently, the development and utilisation of energy efficient control strategies has become of national interest. The objective of this thesis was to demonstrate the utility of the optimised use of ice thermal storage as a DSM strategy in commercial and office buildings in hot arid countries such as Kuwait.

This research work investigated the development of a DSM strategy through the application of ice thermal storage. Load shifting, as one of the well-known DSM techniques, has been investigated. This has been achieved through the utilisation of Model Predictive Control (MPC). The key objective of this thesis was the development of Model Based Predictive Control (MBPC) strategies that involve the logic of knowledge-based control for an integrated and modular approach to the provision of ice thermal storage. A demand response based approach is developed and examined with the involvement of knowledge-based control.

A matlab-simulink model was constructed for the purpose of simulating a building with the characteristics of a Kuwaiti office building. An air-handling unit (AHU) was modelled to represent the HVAC system for the building model. This was discussed and explained in detail in Chapter 5. The modelling of a chiller system with an ice-storage unit and its associated model predictive control (MPC) strategies was the subject of Chapter 6. A logic diagram of the chiller_ice-storage with MPC was illustrated in Chapter 6, Figure 6.8. Figure 6.9 presents a flow diagram describing how the modelled systems link together.

Through the conduct of this researched work; specifically the work in chapters five and six, it was discovered that the issue of non-linearity makes modelling of HVAC system a complicated process. A black box modelling approach was followed for the ice storage component to arrive at the model represented in the mentioned chapters. It was thought that such approach would provide a less complicated modelling environment, the contrary of a modelling process using theoretical or numerical modelling methods. However, the complexity here is not the issue of the modelling of the system itself but rather it relates to the dynamic behaviour of the model, or the set of components that represent the modelled system. This requires clear understanding of the system and its behaviour.

The research work targeted was to develop a strategy that is easily applicable in the case of HVAC systems and not end up introducing a control strategy that is too complicated to adopt or apply. The DSM strategy proposed, if implemented, would be of great benefit towards resolving the problem of the continuous need for the construction of new power plants every few years in Kuwait. Consequently, this is of great interest from a national viewpoint. The development of electricity power demand management strategies are of great importance as the summer peak of consumption continues to expand beyond current generating capacity.

As part of the work, investigation of the effect of specific zones on the building cooling load was conducted through modelling with both the Thermal Analysis Software (TAS) and Matlab. Both models agreed on the difference of the effect of orientation on the building cooling load. Some minor differences between TAS and the implemented Matlab model were discerned, but these were minor and suggested that the Matlab model was adequate for the purposes of this research.

The developed Matlab model showed good behaviour of the implemented integrated ice-storage HVAC system together with model predictive control. The two indoor temperature control strategies introduced were tested through simulation and an examination of their dynamic performance observed. The dynamic behaviour for each strategy was different compared to the other. This is logical and expected, as the indoor temperature to be controlled is a prime candidate to play a role on the performance of an air-conditioning system. The behaviour of each strategy is the reflection of the effect of the different setup of the indoor temperature of a building.

The model with MPC adopted the behaviour of a partial load ice-storage strategy successfully. The results indicated that the model predictive controller was continuously working to optimise the operation of the cooling plant. During the cooler and lower demand periods of the day, the model predictive controller commanded the chiller to operate on a negative chiller output temperature resulting in providing both cooling to the building and charging to the ice-storage. The effect of such control was also indicated on the behaviour of both the ice-storage three-way valve and the AHU three-way valve as shown in Chapter 7. When the demand increased, which reflects a change in the status of occupancy in the building; the chiller is switched to produce a positive temperature outlet by the model predictive controller. In this instance, the chiller is working to provide cooling to the building and at the same time it is discharging the ice-storage to provide the shortage in its capacity by the support from the ice-storage.

The effect of the modelling strategy on the demand curve was investigated. The results presented in Chapter 7 demonstrated the ability of the MPC strategy to facilitate the utilisation of a single chiller instead of two to provide cooling to the building and assign the spare cooling capacity for the charging of the ice-storage. Instead of using a second chiller, the demand that goes beyond the capacity of the chiller is recovered from the stored energy in the ice-storage. This allowed the attainment of a flat demand curve as a result of distributing the load over nearly the twenty-four hours period and not limiting it to a period of few hours during the day.

When transferring electricity from an electricity power generator to a user through the power lines of a transmission grid, energy is lost due to electrical resistances in the power lines [line losses]. In addition, these line losses are higher when the ambient temperature is hotter. Both of these factors lead to line losses being higher during the summer on-peak period. Therefore, an ice-storage system saves energy by shifting electricity use to times of lower line losses when the ambient temperatures are lower. The results in Chapter 7 not only prove this point, but also provide evidence that ice-storage systems when utilised with intelligent control strategies would lead to saving in both the operating and maintenance costs. Moreover, the modelled ice-storage system with MPC leads to minimising the load to save energy while not reducing comfort.

Investigation on the effect of the adopted strategy on the load factor was also examined. The Matlab model performance was compared with a real cooling plant system. Comparison took place on both conventional system operation and an ice-storage assisted HVAC plant operation. The model demonstrated a much improved load factor over the other two cases. However, the model did not account for energy losses from the ice-store over time, for example, and so direct comparison between the modelled and measured results must be made with care.

It is important to highlight that the introduced model provides an investigative tool that allows an examination of different circumstances while studying the cooling plant behaviour. With few modifications the presented model could be accounted as a generalised representation of an integrated ice-storage HVAC system. This is because of the modelling approach that relied mainly on the system input and output data rather than dependence on seeking specific design manufacturer's data to develop a specific ice-storage system.

"When future generations judge those who came before them on environmental issues, they may conclude, "they didn't know": let us not go down in history as the generations who knew, but didn't care" - Mikhail Gorbachev (2002)

8.2 Future Work

The MPC model introduced in this work was shown to be capable of providing prediction of the optimum operation strategy for the system. Yet, an addition is recommended for the model to evaluate the predicted status of the ice-storage, and then provide comparison between the amount of stored energy and the amount consumed. Then to judge the exact amount of energy that should be stored and limit the quantity of energy to be stored to that amount.

As part of artificial intelligence, this work could be linked to employ a neural network predictor for the prediction of cooling demand. In addition, as highlighted this process involves lots of non-linearity in addition to the existence of the uncertainty, accordingly, employing the concept of fuzzy logic could provide an improvement of such system.

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Appendices

Appendix A

APPENDIX A Ice Storage Discharge Tables

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
0	-0.40	-0.54	-0.53	-1.18	0.25	-0.31	-0.36	0.00	-0.44	-0.49	-0.53	0.00	0.00	-0.67
0.33	11.88	15.82	15.93	17.09	19.84	9.40	10.81	12.41	13.35	14.58	15.98	17.79	19.22	20.11
0.43	15.45	20.21	20.70	22.39	25.53	12.22	14.06	16.01	17.36	18.95	20.78	22.96	24.80	26.14
0.53	19.01	23.72	25.48	27.69	31.22	15.04	17.30	19.61	21.36	23.32	25.57	28.12	30.37	32.17
0.91	32.47	40.69	43.52	47.71	52.69	25.69	29.55	33.21	36.48	39.83	43.67	47.62	51.44	54.95
1.01	35.98	45.18	48.29	53.01	58.38	28.51	32.79	36.81	40.49	44.20	48.47	52.78	57.01	60.98
1.02	36.38	45.69	48.83	53.62	59.03	28.83	33.16	37.22	40.94	44.70	49.01	53.37	57.65	61.66
1.06	37.56	46.80	50.44	55.40	60.93	29.77	34.25	38.43	42.29	46.17	50.62	55.10	59.52	63.69
1.11	39.49	48.61	53.07	57.81	64.07	31.33	36.03	40.41	44.49	48.57	53.26	57.95	62.59	67.01
1.12	39.85	48.98	53.62	58.32	64.72	31.65	36.40	40.83	44.95	49.08	53.81	58.54	63.23	67.70
1.16	40.91	50.09	55.04	59.79	66.62	32.59	37.49	42.03	46.29	50.54	55.41	60.27	65.10	69.72
1.22	43.00	52.26	57.86	63.71	70.38	34.46	39.63	44.41	48.94	53.43	58.58	63.68	68.79	73.71
1.25	43.80	53.01	58.83	65.07	71.68	35.10	40.37	45.24	49.85	54.43	59.68	64.86	70.06	75.08
1.32	46.51	55.55	62.11	68.88	76.07	37.28	42.88	48.02	52.94	57.80	63.38	68.85	74.36	79.74
1.33	46.82	55.94	62.61	69.46	76.74	37.61	43.26	48.44	53.41	58.31	63.94	69.45	75.02	80.44
1.41	48.86	58.49	65.91	73.56	81.15	39.80	45.77	51.23	56.52	61.71	67.66	73.46	79.35	85.12
1.42	49.13	58.84	66.44	74.12	81.75	40.10	46.12	51.62	56.95	62.17	68.17	74.01	79.94	85.77
1.42	49.14	58.85	66.45	74.13	81.77	40.10	46.13	51.63	56.96	62.18	68.18	74.02	79.95	85.78
1.42	49.16	58.88	66.48	74.16	81.81	40.12	46.15	51.65	56.98	62.21	68.21	74.06	79.99	85.82
1.43	49.51	59.35	67.02	74.74	82.45	40.43	46.50	52.04	57.42	62.69	68.74	74.62	80.60	86.48
1.5	51.61	62.27	70.31	78.03	86.40	42.30	48.66	54.43	60.08	65.59	71.92	78.05	84.31	90.49
1.51	51.97	62.78	70.82	78.60	87.08	42.63	49.03	54.85	60.54	66.10	72.48	78.65	84.95	91.18
1.52	52.30	63.24	71.28	79.11	87.54	42.92	49.37	55.23	60.96	66.56	72.98	79.19	85.53	91.81
1.52	52.31	63.26	71.30	79.13	87.56	42.94	49.38	55.24	60.98	66.57	73.00	79.21	85.56	91.84
1.53	52.64	63.62	71.75	79.75	88.02	43.23	49.72	55.62	61.39	67.03	73.50	79.75	86.14	92.47
1.6	55.00	65.98	74.70	83.74	90.97	45.12	51.90	58.04	64.08	69.97	76.72	83.22	89.88	96.52
1.61	55.40	66.38	75.38	84.41	91.47	45.44	52.27	58.45	64.54	70.46	77.26	83.80	90.52	97.20
1.61	55.41	66.39	75.39	84.42	91.48	45.45	52.27	58.45	64.55	70.47	77.27	83.81	90.53	97.22
1.62	55.77	66.75	76.01	84.88	92.09	45.74	52.61	58.83	64.96	70.93	77.77	84.35	91.11	97.84
1.63	56.15	67.23	76.65	85.35	92.74	46.05	52.96	59.22	65.40	71.40	78.29	84.91	91.71	98.50
1.69	57.63	69.69	79.98	87.82	96.07	47.63	54.78	61.24	67.65	73.85	80.98	87.81	94.85	101.88
1.7	57.93	70.20	80.49	88.33	96.76	47.96	55.16	61.66	68.11	74.36	81.53	88.41	95.49	102.58
1.71	58.22	70.68	80.97	88.81	97.40	48.26	55.51	62.05	68.55	74.84	82.06	88.97	96.10	103.24
1.72	58.50	71.14	81.43	89.33	98.03	48.56	55.86	62.43	68.97	75.30	82.56	89.52	96.69	103.88
1.73	58.78	71.52	81.90	89.86	98.67	48.87	56.20	62.82	69.40	75.77	83.08	90.07	97.29	104.52
1.79	60.75	73.49	84.37	92.64	102.00	50.45	58.03	64.84	71.65	78.23	85.77	92.97	100.42	107.91
1.79	60.77	73.51	84.39	92.66	102.03	50.47	58.04	64.86	71.67	78.25	85.80	93.00	100.45	107.94
1.8	61.15	73.89	84.77	93.20	102.57	50.77	58.40	65.25	72.11	78.72	86.32	93.56	101.06	108.60
1.82	61.91	74.65	85.53	94.34	103.64	51.38	59.10	66.03	72.97	79.67	87.36	94.68	102.27	109.91
1.83	62.29	75.13	85.91	94.91	104.17	51.69	59.45	66.42	73.40	80.14	87.87	95.23	102.87	110.56
1.88	63.73	77.13	87.51	97.32	106.43	52.97	60.93	68.06	75.23	82.14	90.06	97.59	105.41	113.31
1.89	64.06	77.59	87.88	97.88	106.99	53.27	61.27	68.44	75.66	82.60	90.57	98.14	106.00	113.95

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
1.9	64.42	78.09	88.38	98.48	107.59	53.59	61.64	68.85	76.11	83.10	91.11	98.73	106.64	114.63
1.92	65.11	79.05	89.34	99.55	108.73	54.20	62.34	69.63	76.98	84.04	92.15	99.84	107.84	115.94
1.94	65.80	79.81	90.29	100.63	109.88	54.82	63.05	70.42	77.85	85.00	93.20	100.97	109.06	117.26
1.98	67.01	81.03	91.81	102.34	111.70	55.79	64.17	71.66	79.24	86.51	94.86	102.76	110.99	119.34
1.99	67.38	81.40	92.28	102.86	112.33	56.09	64.51	72.04	79.66	86.97	95.36	103.30	111.58	119.98
1.99	67.39	81.41	92.29	102.87	112.35	56.10	64.52	72.06	79.67	86.98	95.38	103.32	111.60	119.99
2.02	68.54	82.56	93.91	104.31	114.29	57.02	65.58	73.23	80.98	88.41	96.95	105.01	113.42	121.97
2.04	69.31	83.52	94.99	105.27	115.59	57.64	66.29	74.02	81.86	89.37	97.99	106.13	114.64	123.29
2.07	69.92	84.55	96.15	106.30	116.98	58.30	67.06	74.87	82.80	90.40	99.12	107.35	115.95	124.70
2.08	70.20	85.01	96.67	106.76	117.61	58.60	67.40	75.25	83.22	90.86	99.62	107.89	116.54	125.34
2.09	70.50	85.51	97.17	107.27	118.28	58.92	67.77	75.66	83.68	91.36	100.17	108.48	117.17	126.03
2.12	71.36	86.95	98.61	109.21	120.23	59.84	68.83	76.84	84.99	92.79	101.74	110.17	119.00	128.00
2.14	71.93	87.71	99.57	110.50	121.52	60.46	69.53	77.62	85.86	93.74	102.78	111.30	120.21	129.31
2.16	72.37	88.15	100.12	111.24	122.26	60.81	69.94	78.07	86.36	94.29	103.38	111.94	120.91	130.07
2.18	73.13	88.91	101.06	112.52	123.54	61.42	70.64	78.85	87.23	95.23	104.42	113.06	122.12	131.37
2.18	73.14	88.92	101.08	112.54	123.56	61.43	70.65	78.86	87.24	95.24	104.43	113.07	122.13	131.39
2.22	74.68	90.46	103.00	114.71	126.16	62.66	72.07	80.44	88.99	97.16	106.53	115.33	124.58	134.03
2.24	75.44	91.22	103.96	115.78	127.45	63.28	72.78	81.22	89.86	98.11	107.58	116.46	125.79	135.35
2.25	75.49	91.27	104.02	115.86	127.54	63.32	72.82	81.27	89.92	98.17	107.65	116.53	125.87	135.43
2.27	76.18	92.04	104.98	116.94	128.62	63.93	73.53	82.06	90.80	99.13	108.70	117.67	127.09	136.75
2.28	76.52	92.42	105.46	117.51	129.16	64.24	73.88	82.45	91.23	99.60	109.21	118.22	127.70	137.40
2.32	77.91	93.97	107.64	119.83	131.33	65.48	75.31	84.04	93.00	101.53	111.33	120.50	130.15	140.06
2.33	78.30	94.50	108.24	120.47	131.94	65.82	75.71	84.48	93.48	102.06	111.91	121.13	130.83	140.79
2.36	78.95	95.41	109.26	121.57	133.17	66.41	76.38	85.22	94.31	102.97	112.90	122.20	131.99	142.05
2.37	79.37	95.94	109.85	122.20	133.88	66.75	76.77	85.65	94.79	103.49	113.48	122.81	132.66	142.77
2.37	79.38	95.95	109.87	122.22	133.90	66.76	76.78	85.66	94.80	103.51	113.49	122.83	132.67	142.79
2.42	81.31	98.36	112.28	124.93	137.15	68.30	78.56	87.64	97.00	105.90	116.12	125.66	135.73	146.09
2.42	81.35	98.40	112.32	124.98	137.21	68.33	78.59	87.68	97.04	105.95	116.17	125.72	135.79	146.16
2.46	82.46	99.52	113.72	126.55	138.78	69.23	79.62	88.82	98.32	107.34	117.70	127.36	137.57	148.08
2.46	82.50	99.56	113.77	126.61	138.85	69.26	79.66	88.87	98.37	107.39	117.75	127.42	137.63	148.15
2.47	82.88	99.94	114.25	127.08	139.38	69.57	80.01	89.25	98.80	107.86	118.27	127.98	138.23	148.80
2.51	84.47	101.52	115.83	129.07	141.61	70.84	81.48	90.88	100.60	109.84	120.43	130.31	140.75	151.52
2.52	84.82	101.87	116.18	129.51	142.14	71.12	81.80	91.24	101.00	110.27	120.91	130.83	141.31	152.12
2.56	85.97	103.03	117.34	130.95	143.87	72.05	82.86	92.42	102.32	111.71	122.49	132.52	143.14	154.11
2.56	86.00	103.07	117.38	131.00	143.94	72.08	82.91	92.47	102.37	111.77	122.55	132.59	143.21	154.18
2.57	86.25	103.45	117.76	131.64	144.50	72.38	83.25	92.86	102.80	112.23	123.06	133.14	143.81	154.83
2.61	87.32	105.03	119.74	134.32	146.89	73.66	84.72	94.48	104.61	114.21	125.23	135.48	146.33	157.55
2.62	87.56	105.38	120.18	134.91	147.38	73.94	85.04	94.84	105.01	114.65	125.71	135.99	146.89	158.15
2.65	88.10	106.39	121.19	136.28	148.52	74.59	85.79	95.67	105.93	115.65	126.81	137.18	148.17	159.55
2.67	88.60	107.31	122.11	137.20	149.55	75.18	86.47	96.42	106.77	116.57	127.81	138.26	149.34	160.80
2.67	88.63	107.35	122.15	137.24	149.59	75.20	86.50	96.46	106.81	116.61	127.86	138.31	149.39	160.86
2.7	89.83	108.85	123.83	138.74	151.28	76.17	87.60	97.69	108.17	118.10	129.49	140.07	151.29	162.92

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
2.72	90.56	109.77	124.88	139.66	152.39	76.76	88.29	98.44	109.01	119.02	130.50	141.15	152.47	164.19
2.75	91.37	110.58	126.02	140.67	153.61	77.41	89.03	99.27	109.94	120.03	131.61	142.34	153.75	165.58
2.76	91.75	110.96	126.54	141.20	154.17	77.71	89.38	99.66	110.37	120.49	132.12	142.90	154.35	166.22
2.77	92.11	111.32	126.99	141.71	154.71	78.00	89.71	100.02	110.77	120.94	132.61	143.42	154.91	166.83
2.8	93.03	112.55	128.53	143.44	156.56	78.99	90.85	101.29	112.18	122.47	134.29	145.23	156.87	168.95
2.82	93.58	113.28	129.45	144.48	157.59	79.58	91.53	102.04	113.02	123.39	135.29	146.32	158.04	170.22
2.83	93.89	113.60	129.98	145.07	158.19	79.92	91.92	102.48	113.50	123.91	135.87	146.94	158.71	170.94
2.86	94.47	114.17	130.94	146.03	159.26	80.53	92.62	103.26	114.37	124.87	136.91	148.06	159.93	172.25
2.87	94.73	114.44	131.29	146.47	159.76	80.82	92.95	103.62	114.77	125.31	137.40	148.58	160.49	172.86
2.89	95.30	115.07	132.14	147.53	160.95	81.49	93.73	104.49	115.74	126.36	138.55	149.82	161.83	174.31
2.92	96.06	115.91	133.26	148.93	162.85	82.40	94.77	105.64	117.02	127.76	140.09	151.48	163.62	176.25
2.93	96.34	116.44	133.68	149.46	163.57	82.74	95.16	106.08	117.50	128.29	140.66	152.10	164.29	176.97
2.96	96.86	117.40	134.45	150.23	164.86	83.35	95.87	106.86	118.37	129.24	141.71	153.23	165.50	178.29
2.98	97.36	118.33	135.38	150.97	166.12	83.95	96.55	107.62	119.22	130.16	142.72	154.32	166.68	179.56
2.98	97.41	118.41	135.46	151.04	166.23	84.00	96.61	107.69	119.30	130.25	142.81	154.42	166.79	179.68
3.02	98.54	120.30	137.35	152.55	168.12	85.22	98.01	109.25	121.03	132.13	144.88	156.64	169.20	182.28
3.03	98.86	120.49	137.88	152.97	168.65	85.56	98.40	109.68	121.51	132.66	145.46	157.26	169.87	183.00
3.06	99.43	120.83	138.84	153.93	169.61	86.17	99.11	110.46	122.38	133.61	146.50	158.39	171.08	184.32
3.08	99.98	121.17	139.40	154.86	170.54	86.77	99.79	111.22	123.23	134.53	147.51	159.48	172.26	185.59
3.08	100.03	121.20	139.45	154.94	170.62	86.82	99.86	111.30	123.30	134.62	147.61	159.58	172.37	185.71
3.13	101.31	122.05	140.87	157.32	172.57	88.35	101.61	113.25	125.47	136.99	150.20	162.38	175.39	188.98
3.13	101.33	122.08	140.90	157.37	172.60	88.38	101.65	113.28	125.51	137.03	150.25	162.43	175.44	189.03
3.16	101.85	122.84	141.47	158.13	173.38	88.99	102.35	114.06	126.38	137.98	151.29	163.55	176.66	190.35
3.19	102.61	123.98	142.48	159.26	174.54	89.90	103.40	115.22	127.67	139.39	152.84	165.22	178.46	192.29
3.2	103.07	124.44	142.90	159.72	175.01	90.27	103.82	115.70	128.20	139.96	153.47	165.89	179.19	193.08
3.23	104.19	125.56	143.91	160.84	176.13	91.17	104.86	116.85	129.48	141.36	155.00	167.54	180.97	195.01
3.23	104.22	125.59	143.94	160.88	176.17	91.20	104.89	116.88	129.52	141.40	155.04	167.59	181.02	195.06
3.27	105.38	126.74	144.97	162.32	177.32	92.12	105.95	118.06	130.83	142.84	156.62	169.29	182.85	197.05
3.29	106.12	127.49	145.90	163.25	178.06	92.72	106.64	118.83	131.68	143.76	157.63	170.38	184.03	198.32
3.3	106.32	127.95	146.48	163.82	178.52	93.09	107.06	119.30	132.20	144.33	158.26	171.06	184.76	199.11
3.33	106.82	129.07	147.88	165.22	179.92	93.99	108.10	120.45	133.48	145.73	159.79	172.70	186.54	201.04
3.33	106.84	129.09	147.92	165.27	179.97	94.02	108.13	120.48	133.52	145.77	159.84	172.76	186.60	201.10
3.37	107.36	129.87	149.37	166.57	181.41	94.94	109.20	121.67	134.84	147.21	161.41	174.45	188.43	203.08
3.4	107.86	130.63	150.64	167.84	182.82	95.85	110.24	122.82	136.12	148.62	162.95	176.11	190.23	205.02
3.4	107.91	130.67	150.72	167.92	182.91	95.91	110.31	122.90	136.21	148.71	163.05	176.22	190.34	205.14
3.44	108.92	131.69	152.42	169.62	184.42	97.12	111.70	124.45	137.93	150.59	165.11	178.44	192.74	207.73
3.46	109.20	132.10	152.88	170.08	184.83	97.45	112.08	124.87	138.40	151.10	165.68	179.04	193.39	208.44
3.5	110.27	133.69	154.31	171.87	186.42	98.73	113.55	126.50	140.21	153.08	167.85	181.38	195.92	211.17
3.51	110.48	134.01	154.59	172.23	186.80	98.98	113.84	126.82	140.57	153.47	168.28	181.85	196.42	211.72
3.54	111.38	135.20	155.67	173.57	188.24	99.94	114.94	128.05	141.93	154.96	169.91	183.60	198.32	213.76
3.57	111.98	136.00	156.39	174.47	189.20	100.58	115.68	128.87	142.84	155.95	171.00	184.78	199.59	215.14
3.61	113.11	137.52	158.28	176.18	191.02	101.80	117.08	130.42	144.57	157.84	173.07	187.01	202.00	217.74

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
3.64	114.00	138.71	159.78	177.52	192.45	102.76	118.19	131.65	145.94	159.33	174.70	188.77	203.89	219.80
3.67	114.60	139.31	160.78	178.42	193.41	103.40	118.93	132.47	146.85	160.33	175.79	189.94	205.17	221.17
3.71	115.74	140.44	162.91	180.13	195.23	104.62	120.33	134.02	148.58	162.21	177.86	192.17	207.57	223.77
3.74	116.81	141.34	164.59	181.47	196.67	105.58	121.43	135.25	149.94	163.70	179.49	193.93	209.47	225.82
3.76	117.18	141.71	165.18	181.93	197.16	105.91	121.81	135.67	150.41	164.21	180.06	194.54	210.13	226.53
3.82	119.25	143.77	166.72	184.52	199.92	107.75	123.93	138.02	153.02	167.07	183.19	197.91	213.77	230.47
3.85	119.88	144.53	167.29	185.46	200.93	108.43	124.71	138.89	153.99	168.12	184.34	199.15	215.11	231.92
3.86	120.14	144.84	167.52	185.81	201.35	108.71	125.03	139.25	154.39	168.56	184.82	199.67	215.67	232.52
3.87	120.45	145.26	167.80	186.22	201.84	109.04	125.41	139.67	154.86	169.07	185.38	200.27	216.32	233.23
3.92	121.87	147.16	169.36	188.09	204.13	110.57	127.17	141.63	157.03	171.44	187.98	203.07	219.34	236.50
3.96	122.68	148.35	170.33	189.26	205.56	111.53	128.27	142.85	158.39	172.93	189.61	204.83	221.24	238.55
3.99	123.48	149.25	171.31	190.44	207.00	112.48	129.37	144.07	159.75	174.41	191.24	206.58	223.14	240.60
4	123.76	149.56	171.59	190.85	207.51	112.83	129.77	144.51	160.23	174.94	191.82	207.21	223.81	241.33
4.03	124.50	150.38	172.32	191.93	208.59	113.70	130.77	145.62	161.48	176.29	193.30	208.81	225.54	243.20
4.06	125.10	150.98	172.87	192.72	209.40	114.35	131.52	146.45	162.39	177.30	194.40	209.99	226.82	244.58
4.1	126.28	152.05	173.93	194.27	210.98	115.62	132.98	148.07	164.20	179.27	196.56	212.32	229.33	247.30
4.1	126.31	152.07	173.97	194.31	211.02	115.65	133.01	148.11	164.24	179.31	196.61	212.37	229.39	247.36
4.13	127.12	152.80	175.05	195.38	212.32	116.52	134.01	149.22	165.48	180.67	198.10	213.97	231.11	249.23
4.17	127.93	153.61	176.25	196.56	213.76	117.48	135.12	150.45	166.84	182.15	199.73	215.73	233.01	251.28
4.2	128.73	154.80	177.44	197.73	215.19	118.44	136.22	151.67	168.20	183.64	201.36	217.48	234.91	253.33
4.2	128.74	154.82	177.46	197.75	215.21	118.45	136.24	151.69	168.22	183.66	201.38	217.51	234.94	253.36
4.24	129.75	156.31	178.95	199.24	217.00	119.65	137.62	153.22	169.93	185.52	203.42	219.70	237.31	255.93
4.27	130.29	157.12	179.76	200.05	217.97	120.30	138.36	154.05	170.85	186.52	204.52	220.89	238.59	257.31
4.27	130.33	157.18	179.82	200.11	218.04	120.35	138.41	154.11	170.91	186.60	204.60	220.98	238.68	257.41
4.3	131.09	158.31	180.95	201.24	219.18	121.25	139.46	155.27	172.20	188.01	206.15	222.64	240.48	259.36
4.3	131.11	158.33	180.96	201.26	219.20	121.27	139.48	155.29	172.23	188.03	206.18	222.67	240.52	259.39
4.36	132.37	160.21	182.37	203.14	221.08	122.78	141.22	157.22	174.37	190.38	208.74	225.44	243.50	262.63
4.37	132.58	160.63	182.68	203.56	221.49	123.12	141.60	157.65	174.85	190.90	209.31	226.05	244.17	263.34
4.37	132.61	160.67	182.73	203.62	221.55	123.16	141.66	157.71	174.92	190.97	209.40	226.14	244.26	263.44
4.4	133.17	161.43	183.58	204.75	222.57	124.07	142.70	158.87	176.21	192.38	210.94	227.80	246.06	265.39
4.4	133.18	161.44	183.59	204.77	222.59	124.09	142.72	158.90	176.23	192.41	210.97	227.84	246.09	265.42
4.46	134.12	162.71	185.29	206.03	224.28	125.60	144.46	160.82	178.38	194.75	213.54	230.60	249.08	268.65
4.48	134.66	163.25	186.01	206.58	225.01	126.25	145.20	161.65	179.30	195.75	214.64	231.79	250.36	270.04
4.48	134.70	163.31	186.07	206.62	225.06	126.30	145.26	161.71	179.37	195.83	214.72	231.88	250.46	270.14
4.51	135.46	164.44	187.08	207.38	226.19	127.21	146.31	162.88	180.66	197.24	216.27	233.54	252.26	272.09
4.51	135.48	164.46	187.10	207.39	226.21	127.22	146.32	162.90	180.68	197.26	216.29	233.57	252.29	272.12
4.57	136.74	166.34	188.98	209.27	228.09	128.73	148.06	164.82	182.82	199.60	218.86	236.33	255.27	275.35
4.58	137.05	166.76	189.40	209.69	228.51	129.07	148.45	165.25	183.30	200.12	219.43	236.95	255.94	276.07
4.58	137.10	166.80	189.46	209.75	228.57	129.12	148.50	165.32	183.37	200.20	219.51	237.04	256.03	276.18
4.61	137.95	167.56	190.59	210.88	229.70	130.03	149.55	166.48	184.66	201.61	221.06	238.70	257.83	278.12
4.61	137.96	167.58	190.60	210.90	229.72	130.04	149.57	166.50	184.68	201.63	221.09	238.73	257.86	278.15
4.67	139.37	168.84	191.44	212.78	231.60	131.55	151.30	168.42	186.83	203.97	223.65	241.50	260.85	281.38

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
4.68	139.58	169.16	191.66	213.26	232.08	131.94	151.75	168.92	187.37	204.57	224.31	242.20	261.61	282.21
4.69	139.73	169.38	191.80	213.59	232.41	132.20	152.05	169.25	187.75	204.98	224.76	242.69	262.13	282.77
4.71	140.10	170.21	192.17	214.41	233.23	132.86	152.81	170.10	188.69	206.00	225.88	243.90	263.44	284.18
4.72	140.26	170.58	192.34	214.78	233.60	133.16	153.15	170.48	189.11	206.46	226.38	244.44	264.03	284.82
4.78	141.11	172.47	194.23	216.68	235.50	134.68	154.90	172.42	191.27	208.83	228.97	247.23	267.04	288.08
4.78	141.15	172.57	194.33	216.77	235.59	134.75	154.99	172.52	191.38	208.94	229.10	247.37	267.19	288.24
4.79	141.30	172.89	194.65	217.10	235.92	135.02	155.29	172.85	191.75	209.35	229.55	247.85	267.71	288.80
4.81	141.66	173.51	195.48	217.92	236.74	135.68	156.05	173.70	192.69	210.38	230.67	249.06	269.02	290.21
4.82	141.83	173.79	195.85	218.29	237.11	135.98	156.39	174.08	193.11	210.83	231.18	249.60	269.60	290.85
4.88	142.72	175.28	197.84	220.28	239.10	137.57	158.23	176.12	195.38	213.31	233.89	252.53	272.77	294.27
4.89	142.85	175.50	198.13	220.58	239.30	137.81	158.50	176.42	195.72	213.68	234.30	252.96	273.24	294.77
4.89	142.86	175.52	198.16	220.61	239.32	137.84	158.53	176.45	195.75	213.72	234.34	253.01	273.29	294.83
4.91	143.23	175.89	198.99	221.43	239.88	138.50	159.29	177.30	196.69	214.75	235.47	254.22	274.60	296.25
4.92	143.40	176.05	199.36	221.68	240.12	138.79	159.63	177.68	197.11	215.21	235.97	254.77	275.18	296.88
4.99	144.46	177.12	200.96	223.28	241.72	140.71	161.83	180.12	199.83	218.17	239.22	258.26	278.96	300.96
5	144.59	177.25	201.16	223.48	242.02	140.94	162.11	180.42	200.17	218.54	239.62	258.70	279.43	301.47
5	144.62	177.26	201.18	223.50	242.05	140.97	162.13	180.45	200.20	218.58	239.66	258.75	279.48	301.53
5.02	145.23	177.82	201.73	224.06	242.88	141.63	162.90	181.30	201.14	219.60	240.79	259.96	280.79	302.94
5.03	145.51	178.07	201.98	224.33	243.24	141.93	163.24	181.68	201.56	220.06	241.29	260.50	281.38	303.58
5.09	147.00	179.41	203.97	225.82	245.23	143.52	165.08	183.72	203.83	222.54	244.01	263.43	284.54	307.00
5.1	147.22	179.60	204.26	226.04	245.60	143.76	165.35	184.02	204.17	222.91	244.41	263.86	285.01	307.50
5.11	147.41	179.89	204.69	226.36	246.13	144.10	165.74	184.45	204.65	223.43	244.99	264.48	285.68	308.22
5.12	147.60	180.21	205.12	226.68	246.67	144.45	166.14	184.90	205.15	223.97	245.58	265.12	286.37	308.97
5.13	147.77	180.49	205.49	227.02	247.14	144.75	166.48	185.28	205.57	224.43	246.09	265.66	286.95	309.61
5.19	148.66	181.98	206.83	228.81	249.63	146.34	168.32	187.32	207.84	226.91	248.81	268.59	290.12	313.03
5.21	148.96	182.49	207.29	229.42	250.31	146.89	168.95	188.02	208.61	227.76	249.74	269.59	291.20	314.20
5.21	148.98	182.51	207.31	229.45	250.34	146.92	168.98	188.05	208.65	227.80	249.78	269.64	291.25	314.25
5.23	149.34	182.88	207.87	230.19	251.17	147.58	169.74	188.90	209.59	228.83	250.91	270.86	292.56	315.67
5.25	149.51	183.05	208.11	230.47	251.53	147.88	170.08	189.28	210.01	229.29	251.41	271.40	293.15	316.30
5.29	150.22	183.76	209.31	231.67	253.14	149.16	171.56	190.92	211.84	231.28	253.60	273.76	295.69	319.06
5.32	150.70	184.24	210.11	232.47	253.94	150.02	172.55	192.02	213.06	232.61	255.06	275.33	297.39	320.89
5.32	150.72	184.26	210.14	232.49	253.96	150.05	172.58	192.05	213.10	232.66	255.10	275.38	297.44	320.95
5.33	151.02	184.55	210.47	232.82	254.29	150.40	172.98	192.50	213.60	233.20	255.70	276.02	298.14	321.70
5.35	151.27	184.80	210.74	233.07	254.56	150.70	173.32	192.88	214.02	233.66	256.20	276.56	298.72	322.33
5.39	152.34	185.88	211.94	234.14	255.76	151.98	174.80	194.52	215.84	235.65	258.39	278.92	301.27	325.09
5.43	153.33	186.86	213.03	235.13	256.75	153.15	176.15	196.02	217.51	237.47	260.38	281.06	303.59	327.59
5.43	153.33	186.88	213.06	235.15	256.77	153.18	176.18	196.05	217.55	237.51	260.43	281.11	303.64	327.65
5.45	153.44	187.19	213.37	235.43	257.05	153.51	176.56	196.48	218.02	238.03	260.99	281.72	304.30	328.36
5.45	153.44	187.21	213.38	235.44	257.06	153.53	176.58	196.50	218.04	238.06	261.02	281.75	304.33	328.40
5.5	153.93	188.68	214.71	236.92	258.39	155.11	178.40	198.52	220.29	240.51	263.71	284.65	307.46	331.78
5.53	154.19	189.48	215.43	237.72	259.46	155.97	179.39	199.62	221.51	241.84	265.17	286.22	309.16	333.62
5.53	154.21	189.51	215.45	237.74	259.49	156.00	179.42	199.65	221.55	241.88	265.22	286.27	309.21	333.68

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)									
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
5.55	154.50	189.80	215.74	238.07	259.93	156.35	179.83	200.10	222.05	242.43	265.82	286.92	309.91	334.43
5.56	154.75	190.05	215.99	238.32	260.30	156.65	180.17	200.48	222.47	242.88	266.32	287.46	310.49	335.06
5.6	155.83	191.13	217.07	239.40	261.90	157.93	181.65	202.12	224.30	244.88	268.51	289.82	313.04	337.82
5.64	156.81	192.11	218.05	240.38	262.99	159.10	182.99	203.62	225.96	246.69	270.50	291.96	315.35	340.32
5.64	156.83	192.13	218.08	240.40	263.01	159.13	183.02	203.65	226.00	246.74	270.54	292.01	315.41	340.38
5.66	157.02	192.46	218.37	240.69	263.34	159.48	183.43	204.10	226.49	247.28	271.14	292.65	316.10	341.13
5.67	157.19	192.73	218.62	240.97	263.62	159.78	183.77	204.48	226.91	247.74	271.64	293.19	316.69	341.76
5.7	157.73	193.64	219.53	241.88	264.53	160.75	184.89	205.72	228.30	249.25	273.30	294.98	318.62	343.84
5.74	158.40	194.76	220.64	242.99	265.53	161.95	186.27	207.25	230.00	251.11	275.34	297.17	320.99	346.41
5.75	158.55	194.92	220.91	243.26	265.77	162.23	186.59	207.62	230.40	251.55	275.82	297.69	321.55	347.01
5.76	158.57	194.95	220.97	243.32	265.82	162.30	186.67	207.70	230.50	251.65	275.93	297.81	321.68	347.16
5.77	158.65	195.12	221.24	243.57	266.07	162.60	187.01	208.08	230.92	252.11	276.43	298.36	322.26	347.79
5.81	159.01	195.83	221.96	244.65	267.15	163.88	188.49	209.72	232.75	254.11	278.62	300.71	324.81	350.54
5.86	159.33	196.50	222.63	245.65	268.15	165.08	189.87	211.25	234.45	255.96	280.66	302.91	327.18	353.10
5.87	159.41	196.74	222.78	245.89	268.39	165.36	190.19	211.61	234.85	256.40	281.14	303.43	327.74	353.71
5.87	159.45	196.80	222.82	245.95	268.45	165.43	190.27	211.70	234.95	256.51	281.26	303.55	327.87	353.85
5.88	159.61	197.04	222.99	246.19	268.69	165.73	190.61	212.08	235.36	256.96	281.76	304.09	328.46	354.49
5.92	160.33	198.12	224.07	247.27	269.77	167.02	192.09	213.72	237.19	258.96	283.95	306.45	331.01	357.24
5.97	161.00	199.12	225.07	248.28	270.89	168.21	193.47	215.25	238.89	260.82	285.98	308.64	333.37	359.80
5.98	161.15	199.33	225.31	248.51	271.15	168.50	193.80	215.61	239.30	261.26	286.46	309.16	333.93	360.41
5.98	161.20	199.38	225.36	248.57	271.22	168.56	193.87	215.70	239.39	261.36	286.58	309.28	334.07	360.55
5.99	161.38	199.60	225.61	248.75	271.49	168.86	194.21	216.08	239.81	261.82	287.08	309.82	334.65	361.18
6.02	161.98	200.32	226.21	249.36	272.40	169.83	195.33	217.32	241.20	263.33	288.74	311.61	336.58	363.27
6.08	162.90	201.40	227.13	250.27	273.22	171.31	197.04	219.21	243.30	265.63	291.26	314.32	339.51	366.43
6.08	162.94	201.45	227.17	250.31	273.26	171.38	197.11	219.30	243.39	265.73	291.37	314.45	339.64	366.58
6.09	163.10	201.67	227.35	250.56	273.43	171.68	197.45	219.68	243.81	266.19	291.87	314.99	340.23	367.21
6.14	163.82	202.61	228.43	251.64	274.14	172.97	198.94	221.32	245.64	268.19	294.06	317.35	342.78	369.97
6.18	164.48	203.49	229.44	252.64	274.81	174.16	200.31	222.85	247.34	270.04	296.10	319.54	345.14	372.53
6.19	164.64	203.65	229.67	252.88	274.97	174.44	200.64	223.21	247.74	270.48	296.58	320.05	345.70	373.13
6.19	164.68	203.69	229.73	252.94	275.00	174.51	200.72	223.30	247.84	270.59	296.70	320.18	345.84	373.28
6.2	164.84	203.85	229.98	253.21	275.17	174.81	201.06	223.68	248.26	271.05	297.20	320.72	346.42	373.91
6.25	165.56	204.57	231.06	254.41	275.88	176.10	202.54	225.32	250.09	273.04	299.39	323.08	348.97	376.66
6.29	166.22	205.23	232.06	255.53	277.00	177.29	203.91	226.85	251.79	274.90	301.42	325.27	351.34	379.22
6.29	166.25	205.27	232.09	255.57	277.04	177.33	203.96	226.90	251.85	274.96	301.49	325.34	351.41	379.31
6.3	166.38	205.47	232.30	255.70	277.26	177.58	204.24	227.21	252.19	275.34	301.90	325.79	351.90	379.83
6.31	166.58	205.78	232.60	255.90	277.60	177.94	204.66	227.68	252.71	275.90	302.52	326.46	352.62	380.61
6.35	167.13	206.59	233.21	256.45	278.51	178.91	205.78	228.92	254.09	277.41	304.18	328.24	354.55	382.69
6.4	167.97	207.86	234.14	257.29	279.78	180.42	207.51	230.85	256.24	279.75	306.74	331.01	357.53	385.92
6.4	167.99	207.90	234.16	257.31	279.81	180.46	207.56	230.90	256.29	279.81	306.81	331.08	357.61	386.00
6.41	168.12	208.12	234.31	257.51	280.01	180.71	207.84	231.21	256.64	280.19	307.22	331.52	358.09	386.52
6.41	168.15	208.17	234.35	257.55	280.06	180.76	207.90	231.27	256.71	280.27	307.31	331.62	358.19	386.64
6.46	168.87	209.37	235.43	258.63	281.14	182.05	209.38	232.92	258.54	282.27	309.50	333.98	360.74	389.39

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
6.5	169.53	210.49	236.43	259.64	281.80	183.24	210.76	234.45	260.24	284.12	311.54	336.17	363.11	391.95
6.51	169.73	210.68	236.72	259.93	282.00	183.59	211.16	234.90	260.74	284.67	312.13	336.81	363.80	392.70
6.52	169.86	210.82	236.93	260.08	282.13	183.84	211.44	235.21	261.08	285.04	312.55	337.26	364.28	393.22
6.52	169.90	210.85	236.97	260.11	282.16	183.89	211.50	235.27	261.16	285.13	312.64	337.35	364.39	393.33
6.57	170.69	211.56	238.17	260.91	282.88	185.18	212.98	236.92	262.99	287.12	314.83	339.71	366.93	396.09
6.61	171.43	212.23	239.29	261.65	283.62	186.37	214.36	238.45	264.69	288.98	316.86	341.90	369.30	398.65
6.61	171.46	212.26	239.32	261.68	283.64	186.41	214.40	238.50	264.74	289.04	316.93	341.97	369.38	398.73
6.62	171.61	212.46	239.55	261.88	283.79	186.65	214.68	238.81	265.09	289.41	317.34	342.42	369.86	399.25
6.62	171.64	212.51	239.60	261.92	283.82	186.71	214.74	238.87	265.16	289.50	317.43	342.51	369.96	399.36
6.64	171.88	212.88	239.97	262.29	284.10	187.15	215.25	239.43	265.78	290.18	318.17	343.32	370.83	400.30
6.67	172.35	213.59	240.68	263.00	284.62	188.00	216.22	240.52	266.99	291.49	319.62	344.87	372.51	402.12
6.72	173.19	214.85	241.94	264.27	285.46	189.51	217.96	242.45	269.13	293.83	322.18	347.64	375.50	405.35
6.72	173.21	214.88	241.97	264.30	285.48	189.54	218.00	242.50	269.19	293.89	322.25	347.71	375.57	405.43
6.73	173.35	215.03	242.18	264.43	285.62	189.79	218.28	242.81	269.53	294.27	322.66	348.15	376.05	405.95
6.73	173.38	215.06	242.22	264.46	285.65	189.84	218.34	242.87	269.61	294.35	322.75	348.25	376.16	406.06
6.78	174.09	215.86	243.82	265.18	286.36	191.13	219.82	244.52	271.44	296.35	324.94	350.61	378.70	408.81
6.82	174.76	216.60	245.31	265.85	287.03	192.32	221.20	246.05	273.14	298.20	326.97	352.80	381.07	411.37
6.83	174.95	216.78	245.73	266.03	287.22	192.66	221.59	246.48	273.61	298.72	327.55	353.41	381.73	412.09
6.83	174.96	216.79	245.74	266.04	287.22	192.67	221.61	246.50	273.63	298.75	327.57	353.44	381.77	412.13
6.84	175.09	216.93	245.88	266.18	287.36	192.92	221.88	246.80	273.98	299.12	327.98	353.88	382.24	412.64
6.89	175.84	217.67	246.62	266.92	288.10	194.26	223.42	248.52	275.88	301.20	330.26	356.34	384.89	415.51
6.93	176.50	218.34	247.29	267.59	288.43	195.45	224.80	250.05	277.58	303.06	332.30	358.53	387.26	418.07
6.94	176.69	218.62	247.47	267.77	288.52	195.79	225.19	250.47	278.06	303.58	332.87	359.15	387.93	418.79
6.95	176.70	218.63	247.48	267.78	288.53	195.81	225.21	250.49	278.08	303.60	332.90	359.18	387.96	418.82
6.95	176.83	218.83	247.62	267.93	288.60	196.05	225.48	250.80	278.42	303.98	333.31	359.62	388.44	419.34
7	177.58	219.96	248.36	268.76	288.96	197.39	227.02	252.51	280.33	306.05	335.58	362.07	391.09	422.20
7.04	178.24	220.96	249.03	269.50	289.63	198.59	228.40	254.04	282.03	307.91	337.62	364.27	393.46	424.77
7.05	178.26	220.98	249.05	269.53	289.65	198.62	228.45	254.09	282.08	307.97	337.69	364.34	393.53	424.85
7.06	178.43	221.15	249.22	269.69	289.82	198.92	228.79	254.47	282.51	308.43	338.19	364.88	394.12	425.49
7.07	178.57	221.29	249.36	269.84	289.96	199.18	229.09	254.80	282.87	308.83	338.63	365.35	394.63	426.04
7.11	179.40	222.04	250.10	270.58	290.70	200.52	230.63	256.51	284.77	310.91	340.91	367.81	397.28	428.90
7.15	180.04	222.61	250.67	271.15	291.08	201.54	231.80	257.82	286.23	312.50	342.65	369.68	399.31	431.09
7.16	180.14	222.70	250.77	271.25	291.14	201.72	232.00	258.04	286.48	312.77	342.94	370.00	399.65	431.47
7.16	180.17	222.73	250.79	271.27	291.15	201.75	232.05	258.09	286.53	312.83	343.01	370.07	399.73	431.55
7.17	180.32	222.88	250.93	271.40	291.24	202.00	232.33	258.40	286.87	313.20	343.42	370.51	400.20	432.06
7.17	180.35	222.91	250.96	271.43	291.26	202.05	232.39	258.47	286.95	313.29	343.51	370.61	400.31	432.18
7.26	181.73	224.45	251.72	272.81	292.16	204.53	235.25	261.64	290.48	317.14	347.74	375.16	405.23	437.49
7.27	181.92	224.73	251.82	273.00	292.28	204.87	235.63	262.07	290.95	317.66	348.30	375.77	405.89	438.21
7.27	181.92	224.74	251.83	273.01	292.29	204.89	235.65	262.09	290.98	317.68	348.33	375.80	405.92	438.24
7.28	182.06	224.94	252.03	273.08	292.38	205.13	235.93	262.40	291.32	318.06	348.74	376.25	406.40	438.76
7.37	183.47	227.07	254.16	273.77	293.30	207.67	238.85	265.64	294.93	321.99	353.06	380.90	411.42	444.19
7.38	183.66	227.26	254.44	273.86	293.42	208.00	239.23	266.07	295.40	322.51	353.63	381.51	412.08	444.91

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)									
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
7.38	183.67	227.27	254.45	273.87	293.43	208.02	239.25	266.09	295.42	322.53	353.65	381.54	412.11	444.94
7.39	183.80	227.40	254.59	274.00	293.52	208.26	239.53	266.40	295.77	322.91	354.07	381.98	412.59	445.46
7.48	185.93	228.81	256.00	275.42	294.44	210.80	242.45	269.64	299.37	326.85	358.38	386.63	417.61	450.89
7.49	186.21	229.13	256.18	275.60	294.56	211.13	242.83	270.07	299.85	327.37	358.95	387.24	418.28	451.60
7.49	186.22	229.14	256.19	275.61	294.57	211.15	242.85	270.09	299.87	327.39	358.98	387.27	418.31	451.64
7.5	186.42	229.37	256.25	275.68	294.65	211.39	243.13	270.40	300.21	327.77	359.39	387.72	418.79	452.16
7.53	186.71	230.32	256.54	275.96	295.03	212.41	244.31	271.71	301.67	329.35	361.13	389.59	420.81	454.35
7.58	187.04	231.44	256.87	276.29	295.69	213.62	245.69	273.24	303.37	331.22	363.17	391.79	423.19	456.92
7.6	187.21	231.80	257.04	276.46	296.05	214.26	246.43	274.07	304.29	332.22	364.27	392.98	424.47	458.30
7.6	187.22	231.81	257.05	276.47	296.06	214.28	246.45	274.09	304.31	332.24	364.30	393.00	424.50	458.33
7.61	187.28	231.94	257.19	276.60	296.20	214.52	246.73	274.40	304.66	332.62	364.71	393.45	424.98	458.85
7.65	188.24	232.51	257.76	277.17	296.77	215.54	247.91	275.71	306.11	334.21	366.45	395.33	427.01	461.04
7.69	189.36	233.18	258.42	277.84	297.10	216.75	249.29	277.24	307.82	336.07	368.50	397.53	429.38	463.61
7.71	189.91	233.51	258.75	278.17	297.26	217.34	249.97	278.00	308.66	336.99	369.50	398.61	430.55	464.88
7.71	189.92	233.54	258.78	278.20	297.27	217.39	250.03	278.07	308.74	337.07	369.60	398.71	430.66	465.00
7.71	189.93	233.55	258.79	278.21	297.28	217.41	250.05	278.09	308.76	337.10	369.62	398.74	430.69	465.03
7.74	190.13	233.95	259.01	278.41	297.48	218.13	250.88	279.01	309.78	338.22	370.85	400.06	432.12	466.57
7.76	190.28	234.25	259.18	278.56	297.63	218.67	251.51	279.70	310.56	339.06	371.78	401.06	433.20	467.74
7.8	190.61	234.92	259.54	278.89	297.96	219.88	252.89	281.24	312.27	340.93	373.82	403.26	435.58	470.31
7.81	190.70	235.11	259.64	278.98	298.05	220.21	253.27	281.66	312.74	341.44	374.39	403.87	436.23	471.02
7.82	190.77	235.25	259.86	279.05	298.12	220.47	253.57	282.00	313.11	341.84	374.83	404.34	436.75	471.58
7.82	190.81	235.29	259.92	279.07	298.14	220.54	253.65	282.08	313.21	341.95	374.94	404.47	436.88	471.72
7.87	191.51	236.00	260.98	279.46	298.48	221.80	255.11	283.70	315.01	343.91	377.10	406.79	439.39	474.43
7.91	192.18	236.66	261.99	279.82	298.48	223.01	256.49	285.24	316.71	345.78	379.14	408.99	441.77	477.01
7.92	192.37	236.87	262.27	279.93	298.47	223.34	256.88	285.66	317.19	346.30	379.71	409.60	442.43	477.72
7.92	192.37	236.88	262.27	279.93	298.47	223.36	256.89	285.68	317.21	346.32	379.73	409.63	442.46	477.75
7.93	192.51	237.03	262.34	279.93	298.47	223.60	257.17	285.99	317.55	346.70	380.15	410.08	442.94	478.27
7.98	192.88	237.86	262.71	279.92	298.46	224.93	258.71	287.70	319.45	348.77	382.42	412.52	445.58	481.13
8.01	193.12	238.41	262.95	279.91	298.70	225.83	259.73	288.84	320.72	350.15	383.93	414.16	447.34	483.04
8.03	193.30	238.77	263.13	279.90	298.88	226.47	260.48	289.66	321.63	351.15	385.03	415.34	448.62	484.42
8.03	193.30	238.78	263.14	279.90	298.89	226.48	260.49	289.68	321.65	351.17	385.05	415.36	448.65	484.44
8.04	193.37	238.91	263.27	279.97	298.95	226.73	260.77	289.99	322.00	351.55	385.47	415.81	449.13	484.97
8.09	194.61	239.65	264.01	280.34	299.32	228.06	262.31	291.70	323.90	353.62	387.74	418.25	451.77	487.82
8.12	195.44	240.15	264.51	280.58	299.56	228.96	263.34	292.84	325.16	355.00	389.26	419.89	453.54	489.73
8.14	196.00	240.31	264.84	280.75	299.73	229.55	264.02	293.59	326.00	355.92	390.26	420.97	454.71	491.00
8.14	196.01	240.33	264.87	280.76	299.74	229.60	264.08	293.66	326.08	356.01	390.35	421.07	454.81	491.11
8.14	196.01	240.33	264.88	280.76	299.74	229.61	264.09	293.68	326.10	356.02	390.38	421.09	454.84	491.14
8.2	196.45	240.76	265.76	281.64	300.18	231.19	265.91	295.69	328.34	358.47	393.06	423.99	457.96	494.52
8.23	196.69	241.01	266.25	282.14	300.17	232.09	266.94	296.83	329.61	359.86	394.58	425.62	459.73	496.43
8.25	196.85	241.34	266.58	282.47	300.17	232.68	267.62	297.59	330.45	360.78	395.58	426.71	460.90	497.69
8.26	196.88	241.37	266.61	282.50	300.16	232.73	267.68	297.66	330.53	360.86	395.68	426.81	461.01	497.81
8.26	196.89	241.38	266.61	282.50	300.16	232.75	267.69	297.68	330.54	360.88	395.70	426.83	461.03	497.84

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
8.31	197.77	242.25	267.05	282.94	300.15	234.32	269.51	299.69	332.79	363.33	398.38	429.72	464.15	501.21
8.33	197.99	242.47	267.15	283.04	300.26	234.71	269.96	300.19	333.34	363.93	399.05	430.43	464.93	502.05
8.34	198.27	242.75	267.29	283.18	300.40	235.22	270.54	300.83	334.05	364.71	399.90	431.36	465.92	503.12
8.36	198.60	243.08	267.45	283.35	300.56	235.81	271.22	301.59	334.89	365.63	400.91	432.44	467.09	504.39
8.37	198.63	243.11	267.47	283.36	300.57	235.86	271.28	301.66	334.97	365.71	401.00	432.54	467.20	504.50
8.37	198.63	243.12	267.47	283.36	300.58	235.88	271.29	301.67	334.99	365.73	401.02	432.56	467.22	504.53
8.42	199.51	243.99	267.91	283.80	301.01	237.45	273.11	303.69	337.23	368.18	403.70	435.45	470.35	507.91
8.45	200.01	244.49	268.15	284.04	301.00	238.35	274.14	304.83	338.50	369.57	405.22	437.09	472.12	509.82
8.48	200.34	245.04	268.31	284.20	301.00	238.94	274.82	305.59	339.34	370.48	406.23	438.17	473.29	511.09
8.48	200.35	245.09	268.33	284.22	301.00	238.99	274.88	305.66	339.42	370.57	406.32	438.27	473.39	511.20
8.48	200.36	245.10	268.33	284.22	301.00	239.01	274.89	305.67	339.43	370.59	406.34	438.29	473.42	511.23
8.55	200.95	247.12	268.92	284.81	300.98	241.17	277.38	308.43	342.50	373.94	410.02	442.25	477.69	515.85
8.57	201.05	247.22	269.02	284.91	300.98	241.52	277.79	308.89	343.01	374.49	410.62	442.90	478.39	516.61
8.59	201.20	247.37	269.17	285.06	301.13	242.07	278.42	309.59	343.79	375.34	411.55	443.91	479.48	517.78
8.59	201.23	247.38	269.19	285.08	301.14	242.12	278.48	309.65	343.86	375.42	411.64	444.00	479.58	517.90
8.59	201.23	247.38	269.19	285.08	301.15	242.14	278.49	309.67	343.88	375.44	411.66	444.03	479.61	517.92
8.67	202.43	247.98	270.53	286.28	301.74	244.30	280.98	312.43	346.95	378.79	415.34	447.98	483.88	522.55
8.68	202.63	248.17	270.75	286.48	301.84	244.65	281.39	312.88	347.45	379.34	415.94	448.64	484.59	523.31
8.69	202.79	248.34	270.93	286.64	301.84	244.94	281.72	313.25	347.86	379.79	416.43	449.16	485.16	523.92
8.7	202.94	248.48	271.00	286.79	301.83	245.20	282.02	313.58	348.23	380.19	416.87	449.64	485.67	524.48
8.7	202.96	248.52	271.02	286.82	301.83	245.27	282.09	313.67	348.33	380.29	416.99	449.76	485.80	524.62
8.78	203.55	249.72	271.61	287.41	301.82	247.43	284.58	316.43	351.40	383.65	420.66	453.72	490.08	529.24
8.79	203.64	249.92	271.71	287.51	301.81	247.78	284.99	316.88	351.90	384.19	421.26	454.37	490.78	530.00
8.8	203.72	250.08	271.79	287.59	301.81	248.07	285.32	317.25	352.31	384.64	421.76	454.90	491.35	530.62
8.81	203.80	250.22	271.93	287.66	301.81	248.33	285.62	317.58	352.68	385.05	422.20	455.37	491.86	531.17
8.81	203.81	250.26	271.97	287.68	301.81	248.40	285.69	317.67	352.77	385.15	422.31	455.49	491.99	531.31
8.89	204.41	251.46	273.17	288.27	301.79	250.56	288.18	320.43	355.84	388.50	425.98	459.45	496.27	535.94
8.9	204.50	251.66	273.37	288.37	301.79	250.91	288.59	320.88	356.34	389.05	426.58	460.10	496.97	536.69
8.91	204.58	251.82	273.53	288.45	301.79	251.20	288.92	321.25	356.76	389.50	427.08	460.63	497.54	537.32
8.92	204.65	251.96	273.53	288.52	301.78	251.46	289.22	321.58	357.12	389.90	427.52	461.11	498.06	537.87
8.92	204.69	252.00	273.53	288.54	301.78	251.53	289.29	321.66	357.22	390.00	427.63	461.23	498.19	538.01
9	206.03	253.20	273.51	288.52	301.77	253.69	291.78	324.43	360.29	393.35	431.31	465.19	502.46	542.64
9.01	206.25	253.53	273.51	288.52	301.76	254.04	292.19	324.88	360.79	393.90	431.90	465.83	503.16	543.39
9.02	206.40	253.75	273.51	288.52	301.83	254.28	292.46	325.18	361.13	394.27	432.31	466.27	503.63	543.90
9.02	206.41	253.80	273.51	288.52	301.84	254.33	292.52	325.25	361.20	394.35	432.40	466.36	503.73	544.01
9.03	206.50	254.10	273.59	288.51	301.93	254.66	292.89	325.66	361.66	394.85	432.95	466.96	504.38	544.70
9.1	207.01	255.83	274.10	288.50	302.44	256.51	295.02	328.03	364.29	397.73	436.10	470.35	508.04	548.67
9.12	207.19	256.01	274.28	288.49	302.62	257.17	295.79	328.87	365.23	398.75	437.23	471.56	509.35	550.08
9.12	207.21	256.03	274.31	288.49	302.60	257.25	295.87	328.97	365.34	398.87	437.35	471.70	509.50	550.24
9.13	207.26	256.08	274.35	288.49	302.55	257.41	296.06	329.18	365.57	399.12	437.63	472.00	509.82	550.59
9.13	207.27	256.09	274.36	288.49	302.54	257.46	296.12	329.25	365.65	399.20	437.72	472.09	509.93	550.70
9.14	207.36	256.18	274.45	288.49	302.44	257.79	296.49	329.66	366.11	399.71	438.27	472.69	510.57	551.40

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
9.21	207.87	256.69	274.96	289.00	301.91	259.64	298.62	332.03	368.74	402.58	441.42	476.08	514.23	555.36
9.23	208.05	257.05	275.14	289.18	301.72	260.30	299.38	332.87	369.68	403.60	442.55	477.29	515.54	556.78
9.24	208.11	257.19	275.21	289.24	301.78	260.54	299.66	333.18	370.02	403.98	442.95	477.73	516.01	557.29
9.24	208.13	257.22	275.22	289.26	301.80	260.59	299.72	333.24	370.09	404.06	443.04	477.83	516.12	557.40
9.26	208.22	257.40	275.31	289.35	301.88	260.92	300.09	333.66	370.55	404.56	443.59	478.42	516.76	558.09
9.32	208.73	258.43	275.82	289.86	302.39	262.77	302.23	336.02	373.18	407.43	446.74	481.82	520.43	562.06
9.34	208.91	258.61	276.00	290.04	302.57	263.43	302.99	336.87	374.12	408.46	447.87	483.02	521.73	563.47
9.35	208.97	258.68	276.07	290.10	302.57	263.67	303.26	337.17	374.46	408.83	448.27	483.46	522.21	563.98
9.35	208.99	258.69	276.08	290.12	302.57	263.72	303.32	337.24	374.54	408.91	448.36	483.56	522.31	564.10
9.37	209.08	258.78	276.17	290.21	302.57	264.05	303.69	337.66	375.00	409.41	448.91	484.15	522.95	564.79
9.43	209.59	259.29	276.68	290.19	302.55	265.90	305.83	340.02	377.63	412.29	452.07	487.55	526.62	568.75
9.46	209.77	259.65	276.86	290.19	302.55	266.56	306.58	340.87	378.57	413.31	453.19	488.76	527.92	570.16
9.46	209.83	259.79	276.93	290.19	302.55	266.80	306.86	341.17	378.91	413.68	453.60	489.20	528.40	570.68
9.47	209.85	259.82	276.94	290.18	302.55	266.85	306.92	341.24	378.98	413.76	453.69	489.29	528.50	570.79
9.48	209.93	260.00	276.94	290.18	302.54	267.18	307.29	341.65	379.44	414.27	454.24	489.88	529.14	571.48
9.54	210.44	261.03	276.92	290.69	302.53	269.03	309.43	344.02	382.08	417.14	457.39	493.28	532.81	575.45
9.57	210.62	261.21	276.92	290.87	302.52	269.69	310.18	344.86	383.01	418.16	458.51	494.49	534.11	576.86
9.57	210.69	261.28	276.92	290.94	302.59	269.93	310.46	345.17	383.35	418.54	458.92	494.93	534.59	577.37
9.58	210.69	261.29	276.92	290.95	302.60	269.98	310.52	345.24	383.43	418.62	459.01	495.02	534.69	577.49
9.59	210.69	261.38	277.10	291.04	302.69	270.31	310.89	345.65	383.89	419.12	459.56	495.62	535.33	578.18
9.65	210.67	261.89	278.13	291.03	303.20	272.16	313.03	348.02	386.52	421.99	462.71	499.01	539.00	582.15
9.68	210.67	262.07	278.49	291.02	303.38	272.82	313.78	348.86	387.46	423.02	463.83	500.22	540.31	583.55
9.69	210.67	262.13	278.63	291.02	303.38	273.06	314.06	349.17	387.80	423.39	464.24	500.66	540.78	584.07
9.69	210.68	262.15	278.66	291.02	303.38	273.11	314.12	349.24	387.87	423.47	464.33	500.76	540.89	584.18
9.7	210.77	262.24	278.65	291.02	303.38	273.44	314.49	349.65	388.33	423.97	464.88	501.35	541.53	584.87
9.76	211.28	262.75	278.64	291.00	303.36	275.29	316.63	352.02	390.97	426.85	468.03	504.75	545.20	588.84
9.79	211.46	262.74	278.63	291.00	303.36	275.95	317.38	352.86	391.90	427.87	469.15	505.95	546.50	590.25
9.8	211.52	262.74	278.63	290.99	303.36	276.19	317.66	353.17	392.24	428.24	469.56	506.39	546.97	590.76
9.8	211.54	262.74	278.63	290.99	303.36	276.24	317.72	353.23	392.32	428.32	469.65	506.49	547.08	590.88
9.81	211.63	262.74	278.72	290.99	303.35	276.57	318.09	353.64	392.78	428.82	470.20	507.08	547.72	591.57
9.88	212.14	262.72	279.23	290.98	303.34	278.42	320.23	356.01	395.41	431.70	473.35	510.48	551.39	595.54
9.9	212.32	262.90	279.41	290.97	303.33	279.08	320.98	356.85	396.35	432.72	474.47	511.68	552.69	596.94
9.91	212.38	262.97	279.48	290.97	303.40	279.32	321.26	357.16	396.69	433.10	474.88	512.13	553.17	597.46
9.91	212.40	262.98	279.49	290.97	303.41	279.37	321.32	357.23	396.76	433.18	474.97	512.22	553.27	597.57
9.92	212.49	263.07	279.49	290.97	303.50	279.70	321.69	357.64	397.22	433.68	475.52	512.81	553.91	598.26
9.98	212.94	263.52	279.48	291.42	303.96	281.35	323.59	359.75	399.56	436.23	478.32	515.83	557.17	601.79
9.99	212.99	263.58	279.47	291.48	304.01	281.55	323.83	360.01	399.86	436.55	478.67	516.21	557.58	602.23
10.01	213.18	263.76	279.47	291.66	304.19	282.21	324.58	360.85	400.79	437.57	479.79	517.42	558.88	603.64
10.02	213.24	263.83	279.47	291.72	304.19	282.45	324.86	361.16	401.13	437.95	480.20	517.86	559.36	604.15
10.02	213.26	263.84	279.47	291.74	304.19	282.50	324.92	361.23	401.21	438.03	480.29	517.95	559.46	604.27
10.03	213.34	263.93	279.55	291.83	304.19	282.83	325.29	361.64	401.67	438.53	480.84	518.54	560.10	604.96
10.1	213.85	264.44	280.06	291.81	304.17	284.68	327.43	364.01	404.30	441.41	484.00	521.94	563.77	608.93

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
10.12	214.03	264.62	280.24	291.81	304.17	285.34	328.18	364.85	405.24	442.43	485.11	523.15	565.07	610.33
10.13	214.10	264.68	280.31	291.80	304.17	285.58	328.46	365.16	405.58	442.80	485.53	523.59	565.55	610.85
10.13	214.11	264.70	280.32	291.80	304.17	285.63	328.52	365.23	405.65	442.88	485.61	523.69	565.65	610.96
10.14	214.20	264.79	280.32	291.80	304.16	285.96	328.89	365.64	406.11	443.38	486.16	524.28	566.29	611.65
10.21	214.71	265.30	280.31	291.79	304.15	287.81	331.03	368.01	408.75	446.26	489.32	527.68	569.96	615.62
10.23	214.89	265.29	280.30	291.78	304.14	288.47	331.78	368.85	409.68	447.28	490.43	528.88	571.26	617.03
10.24	214.96	265.29	280.30	291.78	304.14	288.71	332.06	369.16	410.03	447.66	490.85	529.32	571.74	617.55
10.24	214.97	265.29	280.30	291.78	304.14	288.76	332.12	369.22	410.10	447.73	490.93	529.42	571.84	617.65
10.25	215.06	265.29	280.30	291.78	304.14	289.08	332.49	369.63	410.56	448.23	491.48	530.01	572.48	618.34
10.31	215.48	265.27	280.29	292.20	304.13	290.63	334.27	371.61	412.75	450.63	494.11	532.84	575.53	621.65
10.34	215.75	265.54	280.28	292.47	304.12	291.60	335.38	372.84	414.12	452.13	495.75	534.61	577.45	623.72
10.35	215.82	265.61	280.28	292.53	304.19	291.84	335.66	373.16	414.47	452.51	496.17	535.06	577.93	624.24
10.35	215.84	265.62	280.28	292.55	304.20	291.89	335.72	373.22	414.54	452.59	496.25	535.15	578.03	624.35
10.37	216.02	265.71	280.36	292.64	304.29	292.21	336.09	373.63	415.00	453.09	496.80	535.74	578.67	625.04
10.42	216.88	266.13	280.79	293.59	304.71	293.76	337.87	375.60	417.19	455.48	499.43	538.57	581.73	628.34
10.45	217.42	266.40	281.05	294.19	304.98	294.73	338.98	376.84	418.57	456.98	501.08	540.34	583.64	630.41
10.46	217.56	266.47	281.12	294.34	304.98	294.97	339.26	377.15	418.92	457.36	501.49	540.79	584.13	630.94
10.46	217.56	266.48	281.13	294.37	304.98	295.02	339.32	377.22	418.99	457.44	501.58	540.88	584.23	631.04
10.47	217.56	266.48	281.13	294.38	304.98	295.03	339.33	377.23	419.00	457.46	501.59	540.90	584.25	631.07
10.53	217.54	266.99	281.12	293.84	304.96	296.89	341.47	379.60	421.64	460.34	504.75	544.30	587.92	635.04
10.57	217.54	267.26	281.11	293.56	304.95	297.86	342.58	380.84	423.01	461.84	506.40	546.07	589.83	637.11
10.57	217.53	267.32	281.11	293.49	305.02	298.10	342.86	381.15	423.36	462.22	506.81	546.52	590.32	637.63
10.58	217.55	267.34	281.11	293.47	305.03	298.15	342.92	381.22	423.43	462.29	506.90	546.61	590.42	637.74
10.58	217.55	267.34	281.11	293.47	305.04	298.16	342.93	381.23	423.45	462.31	506.91	546.63	590.44	637.76
10.64	218.06	267.85	281.62	293.98	305.55	300.02	345.07	383.60	426.08	465.19	510.07	550.03	594.11	641.73
10.68	218.33	268.12	281.89	294.25	305.81	300.99	346.18	384.84	427.46	466.69	511.72	551.81	596.03	643.80
10.69	218.39	268.18	281.95	294.31	305.81	301.23	346.46	385.15	427.81	467.07	512.13	552.25	596.51	644.33
10.69	218.41	268.20	281.97	294.33	305.81	301.28	346.52	385.21	427.88	467.15	512.22	552.35	596.61	644.43
10.69	218.41	268.20	281.97	294.33	305.81	301.29	346.53	385.23	427.89	467.16	512.24	552.36	596.63	644.45
10.75	218.92	268.71	282.48	294.84	305.79	303.15	348.67	387.60	430.53	470.04	515.39	555.77	600.30	648.43
10.79	219.18	268.70	282.75	295.10	305.79	304.12	349.78	388.83	431.90	471.54	517.04	557.54	602.22	650.50
10.8	219.25	268.70	282.81	295.17	305.85	304.36	350.06	389.15	432.25	471.92	517.46	557.99	602.70	651.02
10.8	219.25	268.70	282.83	295.19	305.87	304.41	350.12	389.21	432.32	472.00	517.54	558.08	602.80	651.13
10.8	219.25	268.70	282.83	295.19	305.87	304.42	350.13	389.22	432.34	472.02	517.56	558.10	602.82	651.15
10.86	219.24	268.68	282.81	295.17	306.38	306.28	352.27	391.60	434.97	474.89	520.71	561.50	606.49	655.12
10.9	219.23	268.95	282.80	295.17	306.65	307.25	353.38	392.83	436.35	476.40	522.36	563.27	608.41	657.19
10.91	219.23	269.02	282.80	295.16	306.64	307.49	353.66	393.15	436.70	476.78	522.78	563.72	608.89	657.72
10.91	219.23	269.03	282.80	295.16	306.64	307.54	353.72	393.21	436.77	476.85	522.86	563.81	608.99	657.82
10.91	219.23	269.03	282.80	295.16	306.64	307.55	353.73	393.22	436.78	476.87	522.88	563.83	609.01	657.84
10.98	219.21	269.54	283.31	295.15	306.63	309.41	355.87	395.59	439.42	479.75	526.04	567.23	612.69	661.82
11.02	219.20	269.87	283.65	295.14	306.62	310.62	357.26	397.14	441.14	481.63	528.10	569.45	615.08	664.41
11.02	219.22	269.89	283.66	295.14	306.62	310.67	357.32	397.21	441.21	481.71	528.18	569.54	615.18	664.52

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	2.2	3.3	4.4	5.6	28	32	36	40	44	48	52	56	60
11.02	219.22	269.89	283.66	295.14	306.62	310.68	357.33	397.22	441.23	481.72	528.20	569.56	615.20	664.54
11.08	219.65	270.32	283.65	295.57	306.61	312.25	359.14	399.23	443.46	484.16	530.87	572.44	618.31	667.90
11.08	219.67	270.34	283.65	295.59	306.61	312.33	359.22	399.32	443.56	484.27	531.00	572.57	618.46	668.06
11.09	219.73	270.40	283.65	295.65	306.60	312.54	359.47	399.59	443.87	484.60	531.36	572.96	618.88	668.51
11.13	220.06	270.39	283.64	295.98	306.59	313.75	360.86	401.14	445.59	486.48	533.42	575.18	621.28	671.11
11.13	220.06	270.39	283.64	296.00	306.59	313.80	360.92	401.20	445.66	486.56	533.50	575.27	621.37	671.21
11.13	220.06	270.39	283.64	296.00	306.59	313.81	360.93	401.22	445.67	486.57	533.52	575.29	621.39	671.23
11.19	220.05	270.38	284.07	295.99	306.58	315.38	362.74	403.23	447.91	489.01	536.19	578.17	624.51	674.60
11.2	220.05	270.38	284.15	295.98	306.58	315.67	363.07	403.59	448.31	489.45	536.68	578.69	625.07	675.21
11.24	220.04	270.71	284.48	295.97	306.57	316.88	364.46	405.14	450.03	491.33	538.74	580.91	627.47	677.80
11.24	220.05	270.72	284.49	295.97	306.57	316.93	364.52	405.20	450.10	491.41	538.83	581.01	627.57	677.91
11.24	220.05	270.73	284.49	295.97	306.57	316.94	364.53	405.21	450.12	491.43	538.84	581.02	627.58	677.93
11.3	220.48	271.16	284.48	295.96	306.56	318.51	366.34	407.22	452.35	493.86	541.52	583.90	630.70	681.29
11.31	220.56	271.23	284.48	295.96	306.55	318.80	366.67	407.59	452.76	494.31	542.00	584.43	631.26	681.90
11.35	220.89	271.23	284.47	295.95	306.55	320.01	368.06	409.14	454.48	496.19	544.06	586.65	633.66	684.50
11.35	220.89	271.23	284.47	295.95	306.55	320.06	368.12	409.20	454.55	496.26	544.15	586.74	633.76	684.60
11.35	220.89	271.22	284.47	295.95	306.55	320.07	368.13	409.21	454.56	496.28	544.16	586.75	633.77	684.62
11.41	220.88	271.21	284.90	295.94	306.53	321.64	369.94	411.22	456.79	498.72	546.84	589.64	636.89	687.99
11.42	220.88	271.21	284.98	295.93	306.53	321.93	370.27	411.58	457.20	499.16	547.32	590.16	637.45	688.60
11.46	220.87	271.88	285.31	295.92	306.52	323.14	371.66	413.13	458.92	501.04	549.38	592.38	639.85	691.19
11.46	220.88	271.91	285.33	295.92	306.52	323.19	371.72	413.20	458.99	501.12	549.47	592.47	639.95	691.30
11.46	220.89	271.92	285.33	295.92	306.52	323.20	371.73	413.21	459.01	501.13	549.48	592.49	639.97	691.31
11.52	221.32	272.79	285.76	295.91	306.51	324.77	373.54	415.22	461.24	503.57	552.16	595.37	643.08	694.68
11.53	221.40	272.95	285.84	295.91	306.51	325.06	373.87	415.58	461.65	504.01	552.64	595.89	643.64	695.29
11.57	221.73	272.94	286.17	295.90	306.50	326.27	375.26	417.13	463.37	505.89	554.70	598.11	646.04	697.88
11.58	221.73	272.94	286.19	295.90	306.50	326.32	375.32	417.20	463.44	505.97	554.79	598.20	646.14	697.99
11.58	221.73	272.94	286.19	295.90	306.50	326.33	375.33	417.20	463.45	505.98	554.80	598.22	646.16	698.01
11.63	221.72	272.93	286.17	295.89	306.48	327.90	377.14	419.21	465.68	508.42	557.48	601.10	649.27	701.37
11.64	221.71	272.93	286.17	295.89	306.48	328.19	377.47	419.58	466.09	508.87	557.96	601.62	649.84	701.99
11.68	221.70	272.92	286.16	295.88	306.47	329.40	378.86	421.13	467.81	510.75	560.02	603.84	652.23	704.58
11.69	221.70	272.92	286.16	295.88	306.47	329.45	378.92	421.19	467.88	510.82	560.11	603.94	652.33	704.69
11.69	221.70	272.92	286.16	295.88	306.47	329.46	378.93	421.20	467.89	510.84	560.12	603.95	652.35	704.70
11.74	221.69	272.91	286.60	295.86	306.46	331.03	380.74	423.21	470.13	513.27	562.80	606.83	655.46	708.07
11.75	221.69	272.90	286.67	295.86	306.46	331.32	381.07	423.58	470.54	513.72	563.28	607.35	656.03	708.68
11.8	221.68	273.24	287.01	295.85	306.45	332.53	382.46	425.13	472.26	515.60	565.35	609.57	658.42	711.27
11.8	221.69	273.25	287.02	295.85	306.45	332.58	382.52	425.19	472.33	515.68	565.43	609.67	658.52	711.38
11.8	221.70	273.25	287.02	295.85	306.45	332.59	382.53	425.20	472.34	515.69	565.44	609.68	658.54	711.40
11.85	222.13	273.68	287.45	296.28	306.43	334.16	384.34	427.21	474.57	518.13	568.12	612.56	661.65	714.76
11.86	222.21	273.76	287.53	296.36	306.35	334.45	384.67	427.58	474.98	518.57	568.61	613.09	662.22	715.38
11.91	222.54	273.75	287.87	296.69	306.00	335.66	386.06	429.12	476.70	520.45	570.67	615.31	664.62	717.97
11.91	222.55	273.75	287.88	296.71	305.99	335.71	386.12	429.19	476.77	520.53	570.75	615.40	664.72	718.08
11.91	222.55	273.75	287.88	296.71	305.98	335.72	386.13	429.20	476.78	520.54	570.77	615.41	664.73	718.09

Hours	Storage outlet temperature (Tso)					Discharge Rate (qs)								
	1.1	**2.2**	**3.3**	**4.4**	**5.6**	**28**	**32**	**36**	**40**	**44**	**48**	**52**	**56**	**60**
11.95	222.89	273.74	288.22	297.05	305.63	336.95	387.55	430.77	478.54	522.45	572.86	617.67	667.17	720.73
11.96	222.92	273.74	288.24	297.07	305.60	337.04	387.65	430.89	478.66	522.59	573.01	617.84	667.35	720.92
11.96	222.98	273.74	288.31	297.14	305.53	337.29	387.93	431.20	479.02	522.98	573.44	618.29	667.84	721.45
11.97	222.99	273.74	288.32	297.15	305.52	337.32	387.96	431.24	479.05	523.02	573.48	618.34	667.89	721.51

Appendix B

APPENDIX B Ice Storage Charge Tables

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
8.943	28.732	27.955	27.203	26.198	25.527	24.829	23.972	23.096	29.014	29.583	29.749	30.078
8.945	28.732	27.955	27.203	26.198	25.527	24.829	23.971	23.096	29.014	29.582	29.749	30.078
10.776	28.531	27.750	26.978	26.028	25.339	24.635	23.784	22.908	28.341	29.082	29.374	29.703
11.078	28.498	27.716	26.941	25.999	25.309	24.603	23.753	22.877	28.230	29.000	29.312	29.641
11.083	28.498	27.716	26.940	25.999	25.308	24.603	23.752	22.877	28.228	28.998	29.311	29.640
11.158	28.489	27.707	26.931	25.992	25.300	24.595	23.745	22.869	28.201	28.978	29.296	29.624
11.463	28.454	27.673	26.893	25.964	25.269	24.562	23.713	22.838	28.076	28.895	29.233	29.562
11.771	28.419	27.639	26.856	25.935	25.238	24.530	23.682	22.806	27.962	28.811	29.170	29.499
11.845	28.411	27.631	26.847	25.928	25.230	24.522	23.674	22.799	27.935	28.791	29.155	29.484
11.919	28.402	27.622	26.837	25.921	25.222	24.514	23.667	22.791	27.907	28.770	29.140	29.469
12.226	28.368	27.583	26.800	25.893	25.191	24.482	23.635	22.760	27.794	28.686	29.077	29.406
12.459	28.341	27.553	26.771	25.871	25.167	24.457	23.611	22.736	27.708	28.623	29.029	29.358
12.531	28.332	27.544	26.762	25.864	25.160	24.449	23.604	22.728	27.682	28.603	29.015	29.343
12.608	28.322	27.534	26.753	25.857	25.152	24.441	23.596	22.721	27.653	28.582	28.999	29.328
12.919	28.282	27.495	26.715	25.828	25.120	24.408	23.564	22.689	27.541	28.497	28.935	29.264
13.071	28.263	27.476	26.696	25.814	25.104	24.392	23.549	22.673	27.486	28.456	28.904	29.233
13.906	28.169	27.370	26.593	25.736	25.019	24.304	23.463	22.588	27.184	28.228	28.733	29.062
14.055	28.152	27.351	26.575	25.722	25.004	24.288	23.448	22.572	27.136	28.187	28.703	29.031
14.136	28.143	27.341	26.565	25.715	24.995	24.279	23.440	22.564	27.109	28.165	28.686	29.015
14.287	28.126	27.323	26.546	25.701	24.980	24.263	23.424	22.549	27.059	28.124	28.655	28.984
14.669	28.083	27.280	26.500	25.665	24.941	24.223	23.385	22.510	26.919	28.020	28.577	28.906
14.819	28.066	27.263	26.481	25.651	24.925	24.207	23.370	22.494	26.849	27.979	28.546	28.875
14.824	28.066	27.262	26.480	25.651	24.925	24.206	23.369	22.494	26.847	27.977	28.545	28.874
14.974	28.049	27.242	26.461	25.637	24.910	24.191	23.354	22.478	26.778	27.936	28.515	28.843
15.211	28.022	27.210	26.431	25.615	24.885	24.165	23.330	22.454	26.691	27.872	28.466	28.795
15.356	28.006	27.190	26.412	25.601	24.870	24.150	23.315	22.439	26.637	27.832	28.436	28.765
15.431	27.998	27.180	26.403	25.594	24.863	24.142	23.307	22.432	26.613	27.812	28.421	28.750
15.441	27.997	27.178	26.402	25.593	24.862	24.141	23.306	22.430	26.609	27.809	28.419	28.748
15.512	27.989	27.168	26.394	25.587	24.854	24.134	23.299	22.423	26.586	27.789	28.404	28.733
15.669	27.971	27.148	26.376	25.572	24.838	24.117	23.283	22.407	26.535	27.747	28.372	28.701
15.737	27.963	27.140	26.369	25.566	24.831	24.110	23.276	22.400	26.512	27.728	28.358	28.687
16.124	27.919	27.090	26.326	25.530	24.792	24.069	23.236	22.361	26.369	27.622	28.279	28.608
16.127	27.919	27.090	26.326	25.529	24.791	24.068	23.236	22.360	26.368	27.621	28.279	28.607
16.129	27.918	27.090	26.325	25.529	24.791	24.068	23.236	22.360	26.367	27.621	28.278	28.607
16.585	27.872	27.038	26.275	25.487	24.745	24.020	23.189	22.313	26.197	27.496	28.185	28.513
16.740	27.856	27.020	26.258	25.472	24.729	24.003	23.173	22.297	26.140	27.454	28.153	28.482
16.812	27.848	27.012	26.250	25.466	24.721	23.996	23.166	22.290	26.113	27.435	28.138	28.467
16.959	27.831	26.993	26.233	25.452	24.706	23.980	23.151	22.275	26.059	27.394	28.108	28.437
16.972	27.829	26.991	26.232	25.451	24.705	23.979	23.149	22.274	26.054	27.391	28.106	28.434
17.043	27.821	26.982	26.224	25.444	24.698	23.971	23.142	22.266	26.031	27.371	28.091	28.419
17.265	27.796	26.954	26.199	25.423	24.675	23.948	23.119	22.244	25.958	27.311	28.045	28.374
17.340	27.787	26.944	26.190	25.416	24.667	23.940	23.112	22.236	25.934	27.290	28.030	28.359
17.423	27.778	26.934	26.179	25.409	24.659	23.931	23.103	22.227	25.903	27.268	28.013	28.342
17.429	27.777	26.933	26.178	25.408	24.658	23.931	23.102	22.227	25.901	27.266	28.012	28.341
17.490	27.770	26.926	26.171	25.402	24.652	23.924	23.096	22.221	25.879	27.249	28.000	28.328
17.502	27.769	26.925	26.169	25.401	24.651	23.923	23.095	22.219	25.874	27.246	27.997	28.326
17.583	27.760	26.915	26.159	25.394	24.642	23.914	23.087	22.211	25.844	27.224	27.981	28.309
17.722	27.744	26.900	26.141	25.381	24.628	23.899	23.072	22.197	25.793	27.186	27.943	28.281
17.877	27.726	26.882	26.121	25.366	24.612	23.883	23.057	22.181	25.736	27.144	27.900	28.249

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
17.960	27.717	26.873	26.112	25.359	24.604	23.874	23.048	22.173	25.705	27.121	27.878	28.232
18.041	27.708	26.863	26.102	25.351	24.595	23.866	23.040	22.164	25.675	27.099	27.855	28.215
18.103	27.701	26.856	26.095	25.345	24.589	23.859	23.033	22.158	25.652	27.082	27.841	28.202
18.111	27.700	26.855	26.094	25.345	24.588	23.858	23.033	22.157	25.650	27.080	27.839	28.201
18.117	27.699	26.855	26.094	25.344	24.588	23.858	23.032	22.156	25.648	27.078	27.838	28.200
18.331	27.674	26.830	26.069	25.324	24.566	23.835	23.010	22.135	25.578	27.020	27.788	28.156
18.418	27.664	26.820	26.059	25.314	24.557	23.826	23.001	22.126	25.549	26.996	27.767	28.138
18.485	27.657	26.813	26.052	25.307	24.550	23.819	22.994	22.119	25.527	26.978	27.751	28.124
18.565	27.647	26.804	26.043	25.298	24.542	23.810	22.986	22.111	25.490	26.956	27.733	28.108
18.576	27.646	26.803	26.042	25.297	24.541	23.809	22.985	22.109	25.485	26.953	27.730	28.106
18.790	27.622	26.778	26.017	25.273	24.519	23.786	22.963	22.087	25.386	26.894	27.681	28.062
18.799	27.620	26.777	26.016	25.272	24.518	23.785	22.962	22.087	25.383	26.892	27.679	28.060
18.876	27.612	26.767	26.007	25.264	24.510	23.777	22.954	22.079	25.355	26.871	27.661	28.044
19.253	27.568	26.719	25.965	25.222	24.471	23.737	22.916	22.040	25.216	26.763	27.574	27.967
19.935	27.490	26.632	25.887	25.147	24.401	23.665	22.846	21.970	24.964	26.567	27.417	27.827
19.941	27.489	26.631	25.886	25.147	24.401	23.664	22.845	21.970	24.962	26.566	27.416	27.826
20.084	27.472	26.613	25.868	25.131	24.386	23.649	22.830	21.955	24.909	26.524	27.383	27.797
20.317	27.446	26.583	25.838	25.105	24.362	23.625	22.807	21.931	24.824	26.458	27.329	27.749
20.319	27.445	26.583	25.838	25.105	24.362	23.624	22.807	21.931	24.823	26.457	27.329	27.749
20.404	27.436	26.572	25.827	25.095	24.354	23.615	22.798	21.922	24.795	26.433	27.309	27.732
20.409	27.435	26.571	25.826	25.095	24.353	23.615	22.797	21.922	24.793	26.431	27.308	27.730
20.553	27.419	26.553	25.808	25.078	24.338	23.600	22.783	21.907	24.746	26.392	27.269	27.701
20.563	27.417	26.551	25.807	25.077	24.337	23.598	22.782	21.906	24.743	26.390	27.266	27.699
20.634	27.408	26.542	25.801	25.069	24.330	23.591	22.774	21.899	24.720	26.370	27.247	27.684
20.698	27.400	26.534	25.795	25.062	24.323	23.584	22.768	21.892	24.699	26.352	27.229	27.671
20.849	27.381	26.515	25.781	25.045	24.308	23.568	22.752	21.877	24.643	26.311	27.188	27.640
20.862	27.379	26.513	25.780	25.043	24.306	23.567	22.751	21.875	24.638	26.308	27.184	27.638
20.867	27.378	26.512	25.779	25.042	24.306	23.566	22.750	21.875	24.636	26.306	27.183	27.637
21.007	27.361	26.495	25.767	25.027	24.290	23.551	22.736	21.860	24.585	26.268	27.150	27.608
21.023	27.358	26.492	25.765	25.025	24.288	23.550	22.734	21.859	24.579	26.264	27.146	27.605
21.080	27.351	26.485	25.760	25.018	24.282	23.544	22.729	21.853	24.558	26.248	27.133	27.593
21.174	27.339	26.473	25.751	25.008	24.271	23.534	22.719	21.843	24.523	26.223	27.111	27.574
21.241	27.332	26.465	25.745	25.000	24.263	23.527	22.712	21.837	24.499	26.204	27.096	27.560
21.245	27.331	26.464	25.745	24.999	24.263	23.526	22.712	21.836	24.497	26.203	27.094	27.559
21.320	27.323	26.456	25.736	24.991	24.254	23.518	22.704	21.828	24.469	26.183	27.077	27.544
21.402	27.313	26.446	25.727	24.982	24.245	23.510	22.696	21.820	24.439	26.160	27.058	27.527
21.462	27.306	26.439	25.720	24.975	24.238	23.503	22.689	21.814	24.417	26.144	27.044	27.515
21.537	27.298	26.431	25.712	24.966	24.230	23.495	22.682	21.806	24.391	26.124	27.026	27.500
21.634	27.287	26.420	25.701	24.955	24.221	23.485	22.672	21.796	24.356	26.097	27.002	27.480
21.695	27.280	26.413	25.694	24.948	24.216	23.479	22.666	21.790	24.335	26.081	26.988	27.467
21.778	27.270	26.403	25.684	24.941	24.208	23.470	22.657	21.781	24.305	26.058	26.968	27.450
21.860	27.261	26.394	25.675	24.933	24.201	23.461	22.649	21.773	24.277	26.035	26.948	27.433
21.862	27.261	26.394	25.675	24.933	24.201	23.461	22.648	21.773	24.276	26.035	26.948	27.433
21.929	27.255	26.386	25.667	24.927	24.195	23.454	22.642	21.766	24.252	26.017	26.932	27.419
21.933	27.254	26.386	25.666	24.927	24.195	23.453	22.641	21.766	24.251	26.015	26.931	27.418
22.169	27.233	26.350	25.636	24.905	24.174	23.428	22.617	21.741	24.168	25.951	26.876	27.370
22.236	27.227	26.339	25.628	24.899	24.168	23.421	22.610	21.735	24.144	25.933	26.860	27.355
22.383	27.213	26.317	25.609	24.886	24.155	23.406	22.595	21.720	24.092	25.893	26.826	27.324
22.395	27.212	26.315	25.607	24.884	24.154	23.404	22.594	21.718	24.088	25.889	26.823	27.321

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
22.540	27.199	26.293	25.589	24.866	24.142	23.389	22.579	21.703	24.037	25.850	26.789	27.289
22.545	27.199	26.292	25.588	24.865	24.141	23.389	22.579	21.703	24.035	25.848	26.787	27.288
22.550	27.198	26.291	25.588	24.864	24.141	23.388	22.578	21.702	24.033	25.847	26.786	27.287
22.695	27.183	26.275	25.571	24.846	24.128	23.373	22.563	21.688	23.982	25.807	26.752	27.256
22.836	27.167	26.259	25.555	24.828	24.116	23.358	22.549	21.673	23.932	25.761	26.718	27.225
22.853	27.165	26.257	25.553	24.825	24.114	23.356	22.547	21.671	23.927	25.755	26.714	27.221
22.994	27.150	26.241	25.537	24.807	24.102	23.341	22.532	21.657	23.880	25.709	26.681	27.191
23.076	27.141	26.231	25.528	24.798	24.094	23.332	22.524	21.649	23.854	25.682	26.662	27.173
23.143	27.134	26.224	25.520	24.791	24.089	23.325	22.517	21.642	23.832	25.664	26.646	27.158
23.217	27.126	26.215	25.512	24.782	24.080	23.317	22.510	21.634	23.807	25.644	26.629	27.142
23.228	27.125	26.214	25.510	24.781	24.079	23.316	22.509	21.633	23.803	25.641	26.626	27.140
23.233	27.124	26.214	25.510	24.780	24.078	23.316	22.508	21.633	23.802	25.640	26.625	27.139
23.388	27.107	26.194	25.493	24.763	24.061	23.299	22.492	21.617	23.744	25.598	26.589	27.105
23.599	27.084	26.167	25.470	24.739	24.037	23.277	22.471	21.595	23.667	25.541	26.545	27.059
23.682	27.075	26.156	25.460	24.729	24.027	23.268	22.462	21.586	23.636	25.519	26.528	27.041
23.831	27.059	26.137	25.444	24.716	24.010	23.252	22.447	21.571	23.581	25.479	26.498	27.009
23.844	27.058	26.135	25.443	24.714	24.009	23.251	22.445	21.570	23.576	25.475	26.495	27.006
23.902	27.052	26.129	25.436	24.709	24.004	23.245	22.440	21.564	23.555	25.459	26.483	26.993
23.923	27.049	26.126	25.434	24.707	24.002	23.243	22.437	21.562	23.547	25.454	26.479	26.989
23.981	27.043	26.120	25.428	24.702	23.997	23.236	22.431	21.556	23.526	25.438	26.463	26.976
24.362	27.002	26.076	25.385	24.667	23.962	23.196	22.392	21.517	23.385	25.335	26.359	26.893
24.370	27.001	26.075	25.385	24.666	23.961	23.195	22.392	21.516	23.383	25.333	26.357	26.891
24.381	27.000	26.074	25.383	24.665	23.960	23.194	22.390	21.515	23.379	25.330	26.354	26.889
24.519	26.985	26.059	25.368	24.650	23.948	23.179	22.376	21.501	23.334	25.293	26.316	26.859
24.532	26.983	26.057	25.367	24.648	23.946	23.178	22.375	21.499	23.330	25.289	26.313	26.856
24.614	26.974	26.048	25.358	24.639	23.939	23.169	22.367	21.491	23.303	25.267	26.290	26.838
24.744	26.960	26.033	25.343	24.624	23.927	23.156	22.353	21.478	23.260	25.232	26.255	26.808
24.839	26.950	26.022	25.333	24.613	23.919	23.145	22.344	21.468	23.224	25.206	26.229	26.786
24.986	26.934	26.005	25.317	24.596	23.905	23.130	22.329	21.453	23.168	25.166	26.199	26.751
25.058	26.926	25.997	25.309	24.588	23.899	23.122	22.321	21.446	23.141	25.146	26.184	26.734
25.148	26.916	25.987	25.299	24.580	23.890	23.113	22.312	21.436	23.106	25.122	26.166	26.713
25.150	26.916	25.987	25.299	24.580	23.890	23.113	22.312	21.436	23.106	25.122	26.165	26.713
25.207	26.910	25.980	25.292	24.575	23.885	23.107	22.306	21.430	23.084	25.106	26.154	26.701
25.216	26.909	25.979	25.291	24.574	23.884	23.106	22.305	21.429	23.081	25.103	26.152	26.699
25.220	26.909	25.979	25.291	24.573	23.884	23.105	22.305	21.429	23.079	25.102	26.151	26.698
25.374	26.892	25.959	25.271	24.559	23.866	23.089	22.289	21.413	23.020	25.060	26.119	26.667
25.444	26.884	25.950	25.262	24.553	23.858	23.081	22.282	21.406	22.994	25.041	26.100	26.653
25.683	26.858	25.920	25.231	24.531	23.831	23.056	22.257	21.382	22.903	24.976	26.035	26.604
25.747	26.852	25.911	25.223	24.526	23.824	23.049	22.251	21.375	22.879	24.959	26.018	26.589
25.812	26.844	25.903	25.215	24.518	23.816	23.042	22.244	21.368	22.854	24.941	26.000	26.573
25.827	26.843	25.901	25.213	24.516	23.814	23.041	22.242	21.367	22.849	24.937	25.996	26.569
25.832	26.842	25.901	25.213	24.516	23.814	23.040	22.242	21.366	22.847	24.935	25.994	26.568
25.832	26.842	25.900	25.212	24.516	23.814	23.040	22.242	21.366	22.847	24.935	25.994	26.568
25.895	26.836	25.893	25.205	24.509	23.807	23.034	22.235	21.360	22.827	24.918	25.980	26.553
25.902	26.835	25.892	25.205	24.508	23.806	23.033	22.235	21.359	22.824	24.916	25.978	26.551
25.961	26.828	25.884	25.198	24.501	23.801	23.027	22.229	21.353	22.805	24.900	25.965	26.537
26.119	26.811	25.865	25.180	24.483	23.786	23.010	22.212	21.337	22.753	24.857	25.929	26.500
26.142	26.809	25.862	25.177	24.481	23.784	23.007	22.210	21.335	22.746	24.851	25.924	26.494
26.194	26.803	25.855	25.171	24.475	23.780	23.001	22.205	21.329	22.729	24.836	25.912	26.483

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
26.360	26.785	25.835	25.152	24.456	23.764	22.982	22.188	21.312	22.667	24.791	25.874	26.449
26.435	26.777	25.826	25.144	24.447	23.758	22.974	22.180	21.305	22.640	24.771	25.857	26.434
26.515	26.768	25.816	25.135	24.438	23.750	22.965	22.172	21.296	22.610	24.749	25.839	26.418
26.576	26.762	25.808	25.128	24.431	23.745	22.958	22.166	21.290	22.588	24.732	25.825	26.405
26.583	26.761	25.807	25.127	24.430	23.744	22.957	22.165	21.289	22.584	24.730	25.824	26.404
26.676	26.751	25.796	25.116	24.420	23.736	22.946	22.155	21.280	22.541	24.705	25.802	26.385
26.726	26.745	25.789	25.111	24.414	23.731	22.941	22.150	21.275	22.519	24.691	25.791	26.373
26.807	26.737	25.779	25.102	24.405	23.724	22.932	22.143	21.266	22.481	24.669	25.772	26.354
26.819	26.735	25.778	25.100	24.404	23.723	22.931	22.142	21.265	22.476	24.666	25.770	26.351
26.881	26.729	25.770	25.093	24.397	23.717	22.925	22.136	21.259	22.447	24.649	25.756	26.337
27.123	26.702	25.740	25.066	24.369	23.695	22.903	22.114	21.234	22.358	24.583	25.701	26.280
27.204	26.694	25.730	25.056	24.359	23.688	22.896	22.107	21.226	22.328	24.561	25.682	26.261
27.211	26.693	25.729	25.056	24.358	23.687	22.895	22.106	21.225	22.325	24.559	25.681	26.260
27.262	26.687	25.723	25.050	24.351	23.682	22.890	22.101	21.220	22.306	24.545	25.669	26.249
27.271	26.686	25.722	25.049	24.350	23.681	22.889	22.101	21.219	22.304	24.542	25.667	26.247
27.277	26.686	25.721	25.048	24.349	23.681	22.889	22.100	21.218	22.302	24.541	25.666	26.246
27.414	26.671	25.704	25.033	24.332	23.665	22.876	22.088	21.204	22.257	24.503	25.634	26.218
27.496	26.662	25.694	25.023	24.321	23.656	22.869	22.079	21.196	22.230	24.481	25.616	26.201
27.644	26.646	25.675	25.006	24.302	23.639	22.852	22.064	21.181	22.181	24.441	25.582	26.171
27.734	26.636	25.664	24.996	24.291	23.629	22.842	22.055	21.172	22.148	24.416	25.562	26.153
27.735	26.636	25.664	24.996	24.291	23.629	22.842	22.055	21.171	22.148	24.416	25.561	26.152
27.746	26.635	25.663	24.995	24.290	23.627	22.840	22.054	21.170	22.144	24.413	25.559	26.150
27.892	26.619	25.644	24.978	24.275	23.611	22.824	22.039	21.155	22.090	24.373	25.526	26.120
27.895	26.619	25.644	24.978	24.274	23.610	22.823	22.038	21.155	22.089	24.372	25.525	26.120
27.959	26.612	25.636	24.971	24.268	23.603	22.816	22.032	21.148	22.065	24.354	25.510	26.106
27.972	26.610	25.634	24.970	24.266	23.602	22.815	22.031	21.147	22.060	24.351	25.507	26.104
28.184	26.587	25.610	24.948	24.245	23.583	22.791	22.009	21.125	21.982	24.293	25.456	26.061
28.281	26.577	25.599	24.938	24.235	23.574	22.782	21.999	21.116	21.947	24.267	25.433	26.041
28.353	26.569	25.591	24.931	24.227	23.567	22.775	21.991	21.108	21.920	24.247	25.416	26.026
28.503	26.553	25.574	24.916	24.212	23.554	22.762	21.976	21.093	21.865	24.206	25.375	25.995
28.647	26.537	25.558	24.899	24.197	23.541	22.748	21.961	21.078	21.811	24.167	25.335	25.966
28.660	26.536	25.556	24.898	24.196	23.539	22.747	21.960	21.077	21.807	24.163	25.332	25.963
28.789	26.522	25.541	24.883	24.183	23.524	22.736	21.947	21.063	21.759	24.128	25.297	25.937
28.812	26.519	25.539	24.880	24.180	23.522	22.733	21.945	21.061	21.752	24.122	25.290	25.932
28.816	26.519	25.538	24.880	24.180	23.521	22.733	21.944	21.061	21.751	24.121	25.290	25.931
28.872	26.513	25.532	24.874	24.174	23.515	22.728	21.938	21.055	21.732	24.105	25.278	25.920
29.014	26.497	25.516	24.857	24.160	23.499	22.712	21.924	21.040	21.686	24.067	25.249	25.891
29.096	26.488	25.507	24.848	24.151	23.489	22.702	21.915	21.032	21.659	24.044	25.232	25.874
29.171	26.480	25.498	24.840	24.144	23.481	22.694	21.909	21.024	21.634	24.024	25.217	25.858
29.191	26.478	25.496	24.837	24.142	23.479	22.692	21.907	21.022	21.627	24.018	25.213	25.854
29.335	26.462	25.479	24.821	24.127	23.462	22.675	21.894	21.008	21.573	23.979	25.183	25.825
29.339	26.462	25.479	24.820	24.126	23.462	22.675	21.893	21.007	21.572	23.978	25.183	25.824
29.346	26.461	25.478	24.820	24.126	23.461	22.674	21.893	21.006	21.569	23.976	25.181	25.822
29.348	26.461	25.478	24.819	24.125	23.461	22.674	21.892	21.006	21.569	23.975	25.181	25.822
29.350	26.461	25.478	24.819	24.125	23.461	22.674	21.892	21.006	21.568	23.975	25.180	25.822
29.552	26.439	25.452	24.796	24.105	23.442	22.651	21.874	20.985	21.493	23.920	25.133	25.766
29.560	26.438	25.451	24.795	24.104	23.442	22.650	21.873	20.985	21.491	23.918	25.131	25.764
29.569	26.437	25.450	24.794	24.103	23.441	22.649	21.872	20.984	21.487	23.915	25.129	25.762
29.778	26.414	25.423	24.770	24.079	23.422	22.630	21.853	20.962	21.410	23.858	25.080	25.705

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
29.784	26.414	25.422	24.770	24.078	23.421	22.629	21.853	20.962	21.408	23.856	25.079	25.703
29.797	26.412	25.420	24.768	24.077	23.420	22.628	21.851	20.960	21.403	23.853	25.076	25.700
29.809	26.411	25.419	24.767	24.076	23.419	22.627	21.850	20.959	21.399	23.850	25.073	25.697
29.879	26.404	25.410	24.759	24.068	23.413	22.621	21.842	20.953	21.373	23.830	25.056	25.682
29.881	26.403	25.410	24.759	24.067	23.413	22.620	21.842	20.953	21.372	23.830	25.056	25.682
29.934	26.398	25.403	24.753	24.061	23.408	22.616	21.836	20.948	21.353	23.815	25.043	25.671
29.960	26.395	25.400	24.750	24.058	23.405	22.613	21.833	20.946	21.341	23.808	25.037	25.666
30.024	26.388	25.392	24.743	24.051	23.400	22.607	21.826	20.940	21.311	23.791	25.022	25.653
30.239	26.364	25.368	24.718	24.027	23.380	22.588	21.801	20.920	21.212	23.732	24.970	25.608
30.248	26.364	25.367	24.717	24.026	23.379	22.587	21.800	20.919	21.209	23.730	24.968	25.607
30.255	26.363	25.366	24.716	24.025	23.379	22.586	21.799	20.919	21.207	23.728	24.967	25.605
30.257	26.363	25.366	24.716	24.025	23.378	22.586	21.799	20.919	21.206	23.727	24.966	25.605
30.339	26.354	25.356	24.707	24.015	23.371	22.575	21.790	20.911	21.179	23.705	24.946	25.588
30.344	26.353	25.356	24.706	24.015	23.370	22.575	21.789	20.911	21.178	23.704	24.945	25.587
30.467	26.340	25.342	24.692	24.001	23.359	22.559	21.775	20.899	21.137	23.670	24.917	25.562
30.472	26.339	25.341	24.692	24.000	23.359	22.558	21.774	20.899	21.136	23.668	24.915	25.561
30.567	26.329	25.331	24.681	23.989	23.350	22.546	21.766	20.890	21.105	23.642	24.893	25.541
30.621	26.323	25.324	24.674	23.983	23.345	22.539	21.761	20.885	21.087	23.628	24.881	25.530
30.648	26.320	25.321	24.670	23.980	23.343	22.536	21.759	20.882	21.077	23.620	24.874	25.525
30.712	26.313	25.314	24.662	23.973	23.337	22.528	21.753	20.876	21.052	23.603	24.859	25.512
30.713	26.313	25.314	24.662	23.973	23.337	22.527	21.753	20.876	21.051	23.603	24.859	25.511
30.859	26.297	25.297	24.643	23.956	23.320	22.509	21.739	20.863	20.995	23.563	24.825	25.481
30.874	26.296	25.296	24.641	23.954	23.318	22.507	21.738	20.861	20.989	23.559	24.821	25.478
30.878	26.295	25.295	24.641	23.954	23.318	22.507	21.738	20.861	20.988	23.558	24.820	25.478
30.945	26.288	25.288	24.632	23.946	23.310	22.499	21.731	20.855	20.962	23.539	24.804	25.464
31.160	26.265	25.263	24.605	23.927	23.286	22.475	21.712	20.834	20.879	23.481	24.753	25.420
31.172	26.263	25.262	24.603	23.926	23.285	22.473	21.711	20.833	20.875	23.477	24.750	25.417
31.179	26.263	25.261	24.602	23.925	23.284	22.472	21.710	20.833	20.872	23.476	24.749	25.416
31.332	26.246	25.243	24.586	23.911	23.266	22.455	21.692	20.818	20.813	23.434	24.712	25.385
31.336	26.246	25.243	24.585	23.911	23.266	22.455	21.692	20.818	20.811	23.433	24.711	25.384
31.400	26.239	25.233	24.578	23.905	23.259	22.447	21.685	20.812	20.787	23.415	24.697	25.371
31.413	26.237	25.231	24.577	23.904	23.257	22.446	21.683	20.811	20.781	23.412	24.694	25.368
31.547	26.223	25.211	24.562	23.891	23.244	22.431	21.668	20.798	20.730	23.375	24.663	25.337
31.630	26.214	25.198	24.553	23.884	23.235	22.423	21.658	20.790	20.698	23.352	24.644	25.317
31.633	26.213	25.197	24.553	23.884	23.235	22.423	21.658	20.790	20.697	23.351	24.644	25.317
31.848	26.190	25.164	24.530	23.856	23.213	22.403	21.634	20.770	20.614	23.294	24.595	25.266
31.918	26.182	25.154	24.522	23.847	23.206	22.397	21.627	20.763	20.587	23.276	24.579	25.250
31.947	26.179	25.149	24.519	23.843	23.203	22.394	21.625	20.760	20.575	23.268	24.572	25.243
31.948	26.179	25.149	24.519	23.843	23.203	22.394	21.625	20.760	20.575	23.268	24.572	25.243
32.236	26.148	25.116	24.487	23.807	23.173	22.368	21.598	20.733	20.464	23.191	24.507	25.184
32.245	26.147	25.115	24.486	23.805	23.172	22.367	21.597	20.733	20.461	23.189	24.505	25.182
32.302	26.141	25.108	24.480	23.799	23.166	22.360	21.592	20.727	20.439	23.174	24.492	25.171
32.536	26.115	25.081	24.455	23.772	23.142	22.334	21.571	20.708	20.348	23.111	24.439	25.122
32.924	26.073	25.037	24.413	23.728	23.103	22.290	21.527	20.676	20.199	23.008	24.351	25.043
32.933	26.072	25.036	24.412	23.727	23.102	22.289	21.526	20.675	20.195	23.006	24.349	25.041
33.066	26.058	25.020	24.397	23.715	23.088	22.277	21.511	20.665	20.144	22.970	24.319	25.014
33.157	26.048	25.010	24.387	23.707	23.079	22.268	21.500	20.656	20.109	22.946	24.298	24.995
33.225	26.041	25.002	24.380	23.701	23.072	22.262	21.493	20.650	20.083	22.927	24.283	24.982
33.387	26.023	24.983	24.362	23.686	23.055	22.247	21.478	20.635	20.020	22.883	24.246	24.948

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
33.471	26.014	24.974	24.353	23.678	23.047	22.240	21.470	20.628	19.988	22.860	24.227	24.931
33.612	25.999	24.957	24.338	23.665	23.035	22.227	21.457	20.615	19.934	22.822	24.189	24.902
33.615	25.998	24.957	24.337	23.665	23.034	22.226	21.457	20.615	19.932	22.821	24.188	24.902
33.621	25.998	24.956	24.337	23.664	23.034	22.226	21.457	20.614	19.930	22.819	24.186	24.900
33.625	25.997	24.956	24.336	23.664	23.033	22.225	21.456	20.614	19.928	22.818	24.185	24.900
33.754	25.983	24.941	24.320	23.649	23.022	22.211	21.444	20.602	19.879	22.783	24.150	24.873
33.913	25.966	24.923	24.300	23.631	23.007	22.193	21.430	20.587	19.818	22.740	24.107	24.841
33.930	25.964	24.921	24.297	23.629	23.006	22.191	21.428	20.586	19.811	22.735	24.102	24.837
34.074	25.949	24.904	24.279	23.613	22.993	22.174	21.415	20.573	19.755	22.696	24.072	24.808
34.076	25.949	24.904	24.279	23.613	22.992	22.174	21.415	20.573	19.755	22.695	24.072	24.807
34.237	25.931	24.885	24.258	23.594	22.974	22.156	21.400	20.558	19.693	22.651	24.039	24.774
34.240	25.931	24.885	24.258	23.594	22.974	22.155	21.400	20.558	19.691	22.650	24.038	24.774
34.300	25.924	24.878	24.251	23.587	22.967	22.149	21.395	20.552	19.668	22.634	24.026	24.760
34.309	25.923	24.877	24.250	23.586	22.966	22.148	21.394	20.551	19.665	22.631	24.024	24.758
34.394	25.914	24.867	24.240	23.575	22.956	22.138	21.386	20.544	19.632	22.608	24.007	24.738
34.442	25.909	24.861	24.235	23.569	22.951	22.132	21.382	20.539	19.613	22.595	23.997	24.726
34.464	25.906	24.858	24.232	23.566	22.948	22.130	21.380	20.538	19.605	22.589	23.992	24.721
34.532	25.899	24.850	24.224	23.558	22.941	22.122	21.374	20.533	19.579	22.570	23.977	24.705
34.601	25.892	24.841	24.217	23.549	22.933	22.114	21.367	20.528	19.552	22.552	23.960	24.689
34.764	25.874	24.820	24.198	23.528	22.914	22.096	21.349	20.517	19.489	22.507	23.922	24.651
34.775	25.873	24.819	24.197	23.527	22.913	22.095	21.348	20.517	19.485	22.504	23.920	24.649
34.920	25.857	24.800	24.180	23.508	22.898	22.078	21.331	20.507	19.429	22.464	23.886	24.619
34.925	25.856	24.799	24.180	23.507	22.898	22.078	21.330	20.506	19.427	22.463	23.885	24.618
34.988	25.850	24.791	24.173	23.500	22.891	22.070	21.323	20.502	19.403	22.446	23.870	24.605
34.990	25.849	24.791	24.172	23.500	22.891	22.070	21.323	20.502	19.402	22.445	23.869	24.604
34.999	25.848	24.790	24.171	23.499	22.890	22.069	21.322	20.501	19.399	22.442	23.867	24.603
35.005	25.848	24.789	24.171	23.498	22.889	22.069	21.321	20.501	19.396	22.440	23.866	24.601
35.131	25.834	24.773	24.156	23.484	22.877	22.056	21.307	20.492	19.348	22.399	23.836	24.576
35.289	25.817	24.753	24.138	23.466	22.860	22.040	21.289	20.478	19.287	22.348	23.798	24.543
35.309	25.815	24.750	24.136	23.464	22.858	22.037	21.287	20.476	19.279	22.341	23.793	24.539
35.372	25.808	24.742	24.129	23.457	22.852	22.031	21.281	20.470	19.255	22.320	23.778	24.526
35.375	25.808	24.742	24.128	23.456	22.852	22.031	21.281	20.470	19.254	22.319	23.777	24.526
35.458	25.799	24.731	24.119	23.447	22.842	22.022	21.274	20.462	19.222	22.294	23.758	24.509
35.599	25.783	24.713	24.103	23.431	22.826	22.008	21.261	20.450	19.167	22.250	23.719	24.480
35.608	25.782	24.712	24.102	23.430	22.825	22.007	21.260	20.449	19.164	22.248	23.717	24.478
35.613	25.782	24.711	24.101	23.429	22.825	22.006	21.260	20.448	19.162	22.246	23.715	24.477
35.819	25.760	24.685	24.078	23.401	22.801	21.983	21.241	20.430	19.083	22.183	23.659	24.435
35.830	25.758	24.684	24.077	23.399	22.800	21.981	21.240	20.429	19.078	22.180	23.656	24.432
35.844	25.757	24.682	24.075	23.397	22.798	21.980	21.238	20.427	19.073	22.176	23.652	24.430
35.916	25.749	24.673	24.067	23.388	22.790	21.972	21.232	20.422	19.045	22.156	23.633	24.412
35.977	25.742	24.665	24.060	23.379	22.783	21.965	21.226	20.417	19.022	22.139	23.618	24.398
36.063	25.733	24.654	24.050	23.368	22.773	21.955	21.217	20.410	18.988	22.116	23.598	24.377
36.287	25.709	24.625	24.025	23.337	22.748	21.929	21.191	20.391	18.902	22.055	23.546	24.324
36.288	25.709	24.625	24.025	23.337	22.748	21.929	21.191	20.391	18.902	22.054	23.546	24.324
36.296	25.708	24.624	24.024	23.336	22.747	21.928	21.190	20.390	18.898	22.052	23.544	24.322
36.301	25.707	24.623	24.023	23.335	22.746	21.928	21.190	20.390	18.897	22.051	23.543	24.321
36.303	25.707	24.623	24.023	23.335	22.746	21.928	21.189	20.390	18.896	22.051	23.542	24.320
36.450	25.691	24.604	24.008	23.316	22.729	21.911	21.173	20.378	18.839	22.011	23.508	24.290
36.583	25.677	24.587	23.994	23.299	22.714	21.895	21.157	20.367	18.788	21.975	23.480	24.263

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
36.665	25.668	24.577	23.986	23.289	22.705	21.886	21.148	20.359	18.756	21.953	23.464	24.246
36.751	25.658	24.566	23.977	23.277	22.695	21.876	21.138	20.352	18.723	21.929	23.446	24.228
36.837	25.649	24.555	23.968	23.266	22.687	21.866	21.128	20.344	18.690	21.906	23.428	24.211
36.908	25.641	24.546	23.961	23.257	22.681	21.858	21.120	20.337	18.663	21.887	23.414	24.196
36.912	25.641	24.545	23.961	23.257	22.680	21.858	21.120	20.337	18.661	21.886	23.413	24.195
36.985	25.633	24.536	23.952	23.248	22.674	21.849	21.112	20.330	18.633	21.866	23.398	24.180
37.272	25.602	24.499	23.920	23.214	22.648	21.817	21.079	20.304	18.522	21.789	23.339	24.122
37.353	25.593	24.489	23.910	23.204	22.640	21.807	21.070	20.297	18.491	21.767	23.323	24.105
37.372	25.591	24.486	23.908	23.202	22.638	21.805	21.068	20.295	18.483	21.762	23.319	24.101
37.439	25.584	24.478	23.901	23.194	22.632	21.797	21.061	20.289	18.458	21.744	23.305	24.087
37.520	25.575	24.467	23.891	23.184	22.623	21.788	21.053	20.282	18.426	21.722	23.289	24.071
37.600	25.566	24.457	23.882	23.175	22.614	21.779	21.044	20.274	18.395	21.700	23.269	24.054
37.960	25.527	24.411	23.841	23.132	22.573	21.738	21.008	20.242	18.257	21.603	23.181	23.981
37.965	25.527	24.410	23.841	23.131	22.573	21.737	21.007	20.241	18.255	21.602	23.179	23.980
37.968	25.526	24.410	23.840	23.131	22.572	21.737	21.007	20.241	18.254	21.601	23.178	23.979
37.984	25.525	24.408	23.839	23.129	22.570	21.735	21.005	20.239	18.248	21.597	23.175	23.976
38.127	25.509	24.390	23.822	23.112	22.554	21.718	20.989	20.226	18.192	21.558	23.139	23.942
38.199	25.501	24.380	23.814	23.103	22.546	21.710	20.981	20.220	18.165	21.538	23.122	23.925
38.288	25.492	24.369	23.804	23.093	22.536	21.702	20.970	20.212	18.130	21.514	23.100	23.903
38.427	25.477	24.351	23.788	23.076	22.520	21.690	20.955	20.199	18.077	21.476	23.066	23.870
38.442	25.475	24.349	23.787	23.074	22.518	21.688	20.953	20.198	18.071	21.472	23.062	23.866
38.648	25.453	24.323	23.764	23.050	22.495	21.669	20.929	20.179	17.992	21.415	23.011	23.824
38.653	25.452	24.322	23.763	23.049	22.494	21.669	20.929	20.178	17.990	21.414	23.010	23.823
38.815	25.435	24.301	23.745	23.030	22.476	21.654	20.910	20.160	17.927	21.370	22.970	23.790
38.885	25.427	24.293	23.737	23.021	22.467	21.648	20.903	20.152	17.900	21.351	22.953	23.776
38.887	25.427	24.292	23.737	23.021	22.467	21.648	20.902	20.152	17.899	21.350	22.953	23.775
39.336	25.378	24.235	23.686	22.967	22.409	21.590	20.851	20.101	17.726	21.228	22.842	23.683
39.341	25.378	24.234	23.686	22.967	22.409	21.590	20.851	20.100	17.724	21.226	22.841	23.682
39.343	25.377	24.234	23.686	22.967	22.408	21.589	20.850	20.100	17.723	21.226	22.841	23.682
39.427	25.368	24.223	23.676	22.957	22.397	21.578	20.841	20.092	17.691	21.203	22.820	23.665
39.430	25.368	24.223	23.676	22.956	22.397	21.578	20.841	20.092	17.690	21.202	22.819	23.664
39.498	25.361	24.214	23.668	22.948	22.389	21.569	20.833	20.086	17.664	21.183	22.805	23.650
39.660	25.343	24.193	23.650	22.929	22.371	21.551	20.814	20.071	17.601	21.139	22.772	23.617
39.801	25.328	24.175	23.634	22.907	22.355	21.535	20.798	20.058	17.547	21.101	22.743	23.588
39.965	25.310	24.154	23.616	22.882	22.336	21.516	20.780	20.043	17.484	21.047	22.710	23.555
40.024	25.304	24.147	23.609	22.873	22.330	21.510	20.773	20.038	17.461	21.028	22.694	23.543
40.029	25.303	24.146	23.609	22.872	22.329	21.509	20.772	20.038	17.459	21.026	22.692	23.542
40.115	25.294	24.135	23.599	22.859	22.319	21.499	20.761	20.030	17.426	20.998	22.669	23.524
40.183	25.286	24.126	23.591	22.848	22.311	21.491	20.753	20.024	17.400	20.975	22.650	23.510
40.186	25.286	24.126	23.591	22.848	22.311	21.491	20.752	20.023	17.398	20.974	22.649	23.509
40.271	25.277	24.115	23.581	22.835	22.301	21.481	20.741	20.015	17.366	20.948	22.626	23.492
40.423	25.260	24.096	23.564	22.818	22.284	21.464	20.722	20.002	17.307	20.902	22.585	23.461
40.505	25.251	24.085	23.555	22.808	22.275	21.455	20.711	19.994	17.276	20.877	22.566	23.444
40.640	25.237	24.068	23.540	22.793	22.259	21.439	20.694	19.982	17.223	20.835	22.534	23.412
40.641	25.237	24.068	23.540	22.793	22.259	21.439	20.694	19.982	17.223	20.835	22.534	23.412
40.658	25.235	24.066	23.538	22.791	22.257	21.437	20.692	19.980	17.216	20.830	22.530	23.408
40.712	25.229	24.059	23.531	22.785	22.251	21.431	20.686	19.975	17.196	20.815	22.517	23.396
40.803	25.219	24.047	23.519	22.774	22.241	21.421	20.676	19.965	17.160	20.790	22.496	23.374
40.874	25.211	24.038	23.510	22.766	22.232	21.413	20.667	19.957	17.133	20.770	22.479	23.358

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
40.957	25.202	24.027	23.500	22.757	22.221	21.403	20.658	19.947	17.101	20.748	22.460	23.338
40.959	25.202	24.027	23.499	22.757	22.221	21.403	20.658	19.947	17.100	20.747	22.459	23.338
41.039	25.193	24.017	23.489	22.746	22.211	21.394	20.649	19.938	17.069	20.725	22.440	23.319
41.270	25.168	23.987	23.460	22.717	22.181	21.368	20.622	19.912	16.980	20.661	22.385	23.272
41.400	25.154	23.971	23.443	22.700	22.165	21.353	20.608	19.897	16.930	20.625	22.354	23.245
41.415	25.153	23.969	23.441	22.698	22.163	21.351	20.606	19.896	16.925	20.622	22.350	23.242
41.416	25.153	23.969	23.441	22.698	22.163	21.351	20.606	19.896	16.924	20.621	22.350	23.242
41.562	25.137	23.950	23.422	22.679	22.146	21.335	20.589	19.882	16.868	20.581	22.316	23.212
41.571	25.136	23.949	23.421	22.678	22.145	21.333	20.588	19.882	16.864	20.578	22.314	23.210
41.574	25.135	23.948	23.421	22.678	22.145	21.333	20.588	19.881	16.863	20.578	22.313	23.210
41.950	25.095	23.900	23.372	22.630	22.102	21.285	20.545	19.847	16.718	20.474	22.225	23.120
42.033	25.086	23.890	23.362	22.619	22.092	21.274	20.536	19.839	16.686	20.451	22.205	23.100
42.088	25.080	23.883	23.355	22.612	22.086	21.267	20.529	19.834	16.665	20.436	22.192	23.089
42.103	25.078	23.881	23.353	22.610	22.084	21.265	20.528	19.833	16.659	20.432	22.189	23.086
42.174	25.070	23.872	23.344	22.601	22.075	21.256	20.520	19.825	16.632	20.412	22.172	23.071
42.182	25.070	23.871	23.343	22.600	22.074	21.255	20.519	19.824	16.629	20.410	22.170	23.069
42.567	25.028	23.821	23.294	22.547	22.024	21.211	20.475	19.780	16.480	20.304	22.078	22.991
42.627	25.021	23.814	23.286	22.539	22.016	21.205	20.468	19.773	16.457	20.287	22.064	22.978
42.704	25.013	23.804	23.276	22.529	22.006	21.196	20.459	19.764	16.427	20.266	22.045	22.963
42.776	25.005	23.795	23.267	22.519	21.997	21.188	20.450	19.756	16.400	20.247	22.028	22.948
42.862	24.996	23.784	23.256	22.507	21.986	21.178	20.439	19.748	16.367	20.223	22.007	22.930
42.870	24.995	23.783	23.255	22.506	21.985	21.177	20.438	19.748	16.363	20.221	22.005	22.929
43.085	24.972	23.755	23.227	22.479	21.957	21.149	20.411	19.728	16.281	20.162	21.954	22.885
43.102	24.970	23.753	23.225	22.476	21.955	21.147	20.408	19.726	16.274	20.158	21.950	22.881
43.316	24.947	23.726	23.198	22.449	21.927	21.120	20.381	19.707	16.192	20.099	21.899	22.831
43.464	24.931	23.707	23.179	22.430	21.908	21.101	20.364	19.693	16.134	20.059	21.863	22.796
43.473	24.930	23.705	23.178	22.429	21.907	21.100	20.363	19.692	16.131	20.056	21.861	22.794
43.482	24.929	23.704	23.177	22.428	21.906	21.099	20.362	19.691	16.127	20.054	21.859	22.792
43.543	24.922	23.696	23.169	22.421	21.898	21.092	20.355	19.685	16.104	20.037	21.845	22.778
43.637	24.912	23.684	23.157	22.410	21.885	21.081	20.344	19.674	16.068	20.012	21.822	22.756
44.001	24.872	23.638	23.110	22.369	21.838	21.040	20.303	19.632	15.927	19.912	21.735	22.681
44.004	24.872	23.637	23.110	22.368	21.838	21.039	20.303	19.632	15.926	19.911	21.735	22.681
44.152	24.856	23.618	23.091	22.352	21.819	21.022	20.286	19.615	15.869	19.871	21.699	22.650
44.161	24.855	23.617	23.090	22.351	21.817	21.021	20.285	19.614	15.865	19.868	21.697	22.649
44.170	24.854	23.616	23.088	22.350	21.816	21.020	20.284	19.614	15.862	19.866	21.695	22.647
44.172	24.854	23.616	23.088	22.349	21.816	21.020	20.284	19.613	15.861	19.866	21.694	22.646
44.242	24.846	23.607	23.079	22.338	21.807	21.012	20.276	19.607	15.834	19.846	21.678	22.632
44.396	24.830	23.587	23.060	22.315	21.787	20.995	20.258	19.593	15.775	19.804	21.646	22.601
44.460	24.823	23.579	23.051	22.305	21.778	20.988	20.251	19.587	15.750	19.787	21.633	22.588
44.692	24.797	23.549	23.022	22.269	21.747	20.961	20.224	19.566	15.661	19.724	21.586	22.540
44.707	24.796	23.548	23.020	22.267	21.745	20.959	20.223	19.565	15.655	19.720	21.583	22.537
44.777	24.788	23.539	23.011	22.256	21.735	20.951	20.214	19.558	15.628	19.700	21.568	22.520
44.781	24.788	23.538	23.010	22.256	21.734	20.951	20.213	19.558	15.626	19.699	21.567	22.519
44.841	24.781	23.530	23.003	22.249	21.726	20.944	20.205	19.553	15.604	19.683	21.551	22.506
44.849	24.780	23.529	23.001	22.248	21.725	20.943	20.204	19.552	15.600	19.681	21.548	22.504
44.918	24.773	23.521	22.993	22.240	21.716	20.933	20.196	19.544	15.574	19.662	21.530	22.488
45.084	24.755	23.499	22.971	22.221	21.693	20.907	20.174	19.526	15.510	19.617	21.484	22.449
45.235	24.739	23.480	22.952	22.204	21.674	20.884	20.155	19.509	15.451	19.576	21.443	22.413
45.241	24.738	23.479	22.951	22.203	21.673	20.883	20.154	19.508	15.449	19.574	21.442	22.412

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
45.303	24.731	23.471	22.943	22.196	21.665	20.873	20.146	19.502	15.425	19.558	21.427	22.399
45.461	24.714	23.451	22.923	22.178	21.645	20.849	20.128	19.484	15.364	19.515	21.390	22.367
45.469	24.713	23.450	22.922	22.177	21.644	20.848	20.127	19.483	15.361	19.513	21.388	22.365
45.695	24.689	23.421	22.893	22.148	21.615	20.823	20.102	19.458	15.274	19.452	21.335	22.319
45.770	24.681	23.411	22.884	22.139	21.605	20.814	20.093	19.450	15.245	19.431	21.318	22.304
45.776	24.680	23.411	22.883	22.138	21.604	20.813	20.092	19.449	15.243	19.430	21.316	22.302
45.991	24.657	23.383	22.855	22.111	21.574	20.789	20.068	19.426	15.160	19.371	21.265	22.251
46.081	24.647	23.372	22.844	22.099	21.562	20.779	20.058	19.416	15.125	19.347	21.244	22.230
46.149	24.639	23.363	22.835	22.091	21.553	20.771	20.050	19.408	15.099	19.329	21.227	22.213
46.228	24.631	23.353	22.825	22.081	21.542	20.761	20.041	19.400	15.068	19.307	21.208	22.194
46.234	24.630	23.352	22.824	22.080	21.541	20.760	20.040	19.399	15.066	19.306	21.207	22.193
46.383	24.614	23.333	22.805	22.061	21.521	20.741	20.023	19.382	15.009	19.265	21.172	22.161
46.679	24.582	23.295	22.767	22.024	21.483	20.703	19.990	19.350	14.894	19.185	21.103	22.096
46.760	24.573	23.285	22.757	22.014	21.473	20.693	19.979	19.341	14.863	19.163	21.084	22.079
46.763	24.573	23.284	22.757	22.013	21.472	20.692	19.979	19.341	14.862	19.163	21.083	22.078
46.828	24.566	23.276	22.748	22.005	21.464	20.685	19.971	19.333	14.837	19.145	21.068	22.064
46.995	24.548	23.255	22.727	21.984	21.443	20.666	19.949	19.314	14.773	19.100	21.028	22.028
47.056	24.541	23.247	22.719	21.976	21.433	20.659	19.941	19.307	14.749	19.083	21.013	22.015
47.221	24.523	23.226	22.698	21.955	21.408	20.640	19.920	19.289	14.685	19.039	20.974	21.979
47.291	24.516	23.217	22.689	21.947	21.397	20.632	19.911	19.281	14.659	19.020	20.958	21.964
47.448	24.499	23.197	22.669	21.927	21.373	20.614	19.893	19.263	14.598	18.977	20.921	21.930
47.516	24.491	23.188	22.660	21.918	21.363	20.604	19.886	19.255	14.572	18.959	20.905	21.915
47.606	24.481	23.176	22.649	21.907	21.349	20.590	19.876	19.243	14.537	18.934	20.884	21.896
47.756	24.465	23.157	22.630	21.888	21.332	20.567	19.858	19.222	14.479	18.894	20.849	21.863
47.975	24.441	23.129	22.601	21.860	21.307	20.534	19.834	19.192	14.395	18.835	20.789	21.816
47.979	24.441	23.129	22.601	21.860	21.306	20.533	19.833	19.192	14.393	18.834	20.788	21.815
48.060	24.432	23.118	22.591	21.850	21.297	20.521	19.824	19.181	14.362	18.812	20.766	21.797
48.214	24.416	23.099	22.571	21.830	21.280	20.503	19.806	19.160	14.303	18.770	20.724	21.764
48.294	24.407	23.088	22.561	21.820	21.271	20.494	19.797	19.149	14.272	18.748	20.707	21.746
48.667	24.366	23.041	22.513	21.773	21.223	20.451	19.755	19.098	14.128	18.647	20.631	21.666
48.748	24.358	23.030	22.503	21.763	21.212	20.442	19.744	19.087	14.097	18.626	20.614	21.648
48.749	24.358	23.030	22.502	21.763	21.212	20.442	19.744	19.087	14.096	18.625	20.614	21.648
48.832	24.349	23.020	22.492	21.752	21.202	20.432	19.734	19.075	14.064	18.603	20.592	21.630
48.906	24.341	23.010	22.482	21.743	21.192	20.422	19.724	19.065	14.036	18.583	20.571	21.615
49.062	24.324	22.990	22.462	21.723	21.171	20.402	19.704	19.044	13.976	18.541	20.529	21.583
49.207	24.308	22.972	22.444	21.705	21.151	20.384	19.686	19.024	13.920	18.501	20.489	21.553
49.278	24.300	22.962	22.435	21.696	21.141	20.374	19.677	19.015	13.892	18.482	20.473	21.538
49.359	24.291	22.952	22.424	21.685	21.130	20.364	19.667	19.003	13.861	18.460	20.455	21.522
49.367	24.291	22.951	22.423	21.684	21.129	20.363	19.667	19.002	13.858	18.458	20.453	21.520
49.594	24.266	22.922	22.394	21.655	21.098	20.333	19.641	18.972	13.771	18.397	20.402	21.474
49.674	24.257	22.912	22.384	21.645	21.088	20.323	19.632	18.961	13.740	18.375	20.384	21.457
49.902	24.233	22.883	22.355	21.610	21.059	20.293	19.606	18.929	13.652	18.313	20.332	21.411
49.967	24.226	22.874	22.347	21.600	21.051	20.284	19.598	18.921	13.627	18.296	20.318	21.396
50.205	24.200	22.844	22.316	21.564	21.020	20.253	19.568	18.888	13.535	18.231	20.264	21.340
50.285	24.191	22.834	22.306	21.551	21.008	20.242	19.558	18.877	13.504	18.210	20.246	21.321
50.436	24.175	22.814	22.286	21.534	20.985	20.222	19.538	18.856	13.446	18.169	20.211	21.286
50.578	24.159	22.796	22.268	21.518	20.963	20.204	19.520	18.837	13.391	18.130	20.179	21.257
50.817	24.133	22.766	22.238	21.491	20.926	20.172	19.493	18.805	13.299	18.066	20.125	21.208
50.971	24.117	22.746	22.218	21.473	20.902	20.152	19.475	18.783	13.239	18.024	20.091	21.176

qs	Storage delta T, dTs							Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
50.973	24.116	22.746	22.218	21.473	20.902	20.152	19.475	18.783	13.239	18.023	20.090	21.176
51.266	24.085	22.708	22.180	21.440	20.857	20.113	19.442	18.743	13.126	17.944	20.024	21.106
51.423	24.068	22.688	22.160	21.422	20.833	20.092	19.424	18.722	13.065	17.902	19.989	21.068
51.428	24.067	22.687	22.160	21.421	20.832	20.092	19.423	18.721	13.063	17.900	19.987	21.067
51.429	24.067	22.687	22.159	21.421	20.832	20.092	19.423	18.721	13.063	17.900	19.987	21.067
51.500	24.059	22.678	22.150	21.413	20.824	20.082	19.415	18.711	13.036	17.881	19.968	21.052
51.881	24.018	22.629	22.102	21.370	20.781	20.039	19.372	18.659	12.889	17.778	19.863	20.974
51.954	24.010	22.620	22.092	21.361	20.772	20.031	19.363	18.649	12.860	17.758	19.846	20.959
51.964	24.009	22.619	22.091	21.360	20.771	20.029	19.362	18.648	12.856	17.755	19.844	20.957
52.116	23.992	22.599	22.072	21.343	20.754	20.012	19.343	18.627	12.798	17.714	19.808	20.922
52.188	23.985	22.590	22.062	21.335	20.745	20.004	19.334	18.617	12.770	17.695	19.792	20.905
52.416	23.960	22.561	22.033	21.309	20.716	19.975	19.304	18.586	12.682	17.633	19.738	20.852
52.499	23.951	22.550	22.023	21.299	20.705	19.964	19.294	18.575	12.650	17.611	19.718	20.832
52.566	23.944	22.542	22.014	21.292	20.696	19.956	19.285	18.566	12.625	17.593	19.702	20.818
52.727	23.926	22.521	21.993	21.273	20.676	19.935	19.263	18.544	12.562	17.549	19.664	20.785
52.799	23.918	22.512	21.984	21.265	20.666	19.926	19.253	18.534	12.534	17.529	19.647	20.771
52.874	23.910	22.502	21.975	21.257	20.656	19.917	19.243	18.524	12.506	17.509	19.629	20.755
53.034	23.893	22.482	21.954	21.239	20.635	19.899	19.221	18.502	12.444	17.466	19.591	20.723
53.254	23.869	22.454	21.926	21.214	20.605	19.874	19.191	18.472	12.359	17.406	19.540	20.676
53.409	23.852	22.434	21.906	21.196	20.584	19.856	19.177	18.451	12.300	17.364	19.504	20.644
53.487	23.844	22.424	21.896	21.187	20.573	19.847	19.170	18.440	12.269	17.343	19.485	20.627
53.867	23.803	22.375	21.847	21.144	20.522	19.789	19.135	18.388	12.123	17.240	19.394	20.547
53.942	23.795	22.366	21.838	21.135	20.512	19.778	19.129	18.378	12.094	17.220	19.377	20.531
54.099	23.778	22.346	21.818	21.117	20.491	19.754	19.105	18.357	12.033	17.178	19.340	20.498
54.402	23.745	22.307	21.779	21.083	20.450	19.719	19.058	18.315	11.917	17.096	19.269	20.434
54.553	23.728	22.287	21.760	21.066	20.430	19.702	19.035	18.295	11.858	17.055	19.233	20.402
54.787	23.703	22.258	21.730	21.039	20.398	19.675	19.013	18.263	11.768	16.992	19.177	20.353
54.860	23.695	22.248	21.720	21.031	20.389	19.666	19.007	18.253	11.740	16.972	19.160	20.337
55.241	23.654	22.199	21.672	20.987	20.337	19.617	18.972	18.201	11.593	16.869	19.070	20.257
55.395	23.637	22.180	21.652	20.970	20.316	19.598	18.953	18.180	11.534	16.827	19.035	20.225
55.398	23.637	22.179	21.651	20.970	20.316	19.597	18.953	18.179	11.532	16.826	19.034	20.224
55.555	23.620	22.159	21.631	20.952	20.295	19.576	18.934	18.158	11.472	16.784	18.997	20.191
55.632	23.611	22.149	21.622	20.943	20.285	19.565	18.924	18.147	11.442	16.763	18.980	20.173
56.086	23.562	22.091	21.563	20.891	20.223	19.503	18.868	18.085	11.267	16.640	18.875	20.066
56.090	23.562	22.091	21.563	20.891	20.222	19.503	18.868	18.085	11.266	16.639	18.874	20.066
56.320	23.537	22.061	21.533	20.865	20.191	19.473	18.840	18.053	11.177	16.577	18.821	20.019
56.625	23.504	22.022	21.495	20.830	20.152	19.434	18.802	18.012	11.059	16.494	18.750	19.956
56.698	23.496	22.013	21.485	20.822	20.142	19.425	18.793	18.002	11.031	16.475	18.733	19.939
56.932	23.470	21.983	21.455	20.795	20.112	19.389	18.764	17.970	10.941	16.411	18.679	19.883
57.083	23.454	21.964	21.436	20.778	20.092	19.366	18.746	17.949	10.883	16.370	18.644	19.847
57.309	23.429	21.935	21.407	20.752	20.061	19.331	18.718	17.918	10.795	16.309	18.592	19.800
57.535	23.405	21.906	21.378	20.727	20.030	19.305	18.690	17.888	10.708	16.248	18.540	19.754
57.618	23.396	21.895	21.367	20.717	20.019	19.296	18.680	17.876	10.676	16.226	18.521	19.737
57.619	23.396	21.895	21.367	20.717	20.018	19.296	18.679	17.876	10.676	16.225	18.520	19.737
57.763	23.380	21.877	21.349	20.701	19.999	19.279	18.661	17.856	10.620	16.186	18.487	19.703
57.997	23.355	21.847	21.319	20.674	19.967	19.253	18.631	17.824	10.530	16.123	18.433	19.648
58.146	23.339	21.828	21.300	20.657	19.947	19.234	18.612	17.804	10.473	16.083	18.399	19.614
58.152	23.338	21.827	21.299	20.656	19.946	19.233	18.611	17.803	10.470	16.081	18.397	19.612
58.609	23.289	21.768	21.241	20.604	19.883	19.174	18.553	17.741	10.294	15.957	18.292	19.519

qs	Storage delta T, dTs								Flow rate			
	3	4	5	6	7	8	9	10	80	120	160	200
58.687	23.280	21.758	21.231	20.595	19.873	19.164	18.543	17.730	10.264	15.936	18.273	19.503
59.222	23.222	21.690	21.162	20.535	19.800	19.091	18.474	17.657	10.058	15.791	18.150	19.393
59.297	23.214	21.680	21.153	20.526	19.790	19.081	18.465	17.647	10.029	15.771	18.133	19.378
59.757	23.164	21.621	21.094	20.474	19.727	19.022	18.406	17.584	9.851	15.647	18.026	19.284
59.908	23.148	21.602	21.074	20.456	19.706	19.002	18.387	17.564	9.793	15.606	17.991	19.253
60.292	23.106	21.553	21.025	20.413	19.654	18.959	18.337	17.511	9.645	15.502	17.903	19.174
60.596	23.073	21.514	20.986	20.378	19.612	18.924	18.299	17.470	9.528	15.420	17.832	19.103
60.826	23.048	21.485	20.957	20.352	19.581	18.889	18.269	17.438	9.439	15.357	17.779	19.049
61.208	23.007	21.436	20.908	20.309	19.529	18.830	18.220	17.386	9.292	15.254	17.691	18.971
61.361	22.990	21.416	20.888	20.291	19.508	18.810	18.201	17.365	9.233	15.213	17.655	18.939
64.112	22.692	21.064	20.536	19.978	19.132	18.449	17.849	16.990	8.172	14.468	17.020	18.361
64.189	22.684	21.054	20.526	19.969	19.122	18.439	17.839	16.979	8.142	14.448	17.002	18.343
64.646	22.634	20.996	20.468	19.917	19.059	18.387	17.780	16.917	7.966	14.324	16.896	18.236
64.877	22.609	20.966	20.438	19.891	19.028	18.361	17.751	16.885	7.877	14.261	16.843	18.188
65.105	22.584	20.937	20.409	19.865	18.997	18.326	17.722	16.854	7.789	14.200	16.790	18.142
65.488	22.543	20.888	20.360	19.822	18.944	18.267	17.672	16.802	7.641	14.096	16.701	18.063
66.176	22.468	20.800	20.272	19.743	18.850	18.188	17.584	16.708	7.376	13.910	16.542	17.922

Appendix C

APPENDIX C Matlab-Simulink Building Model with HVAC Model

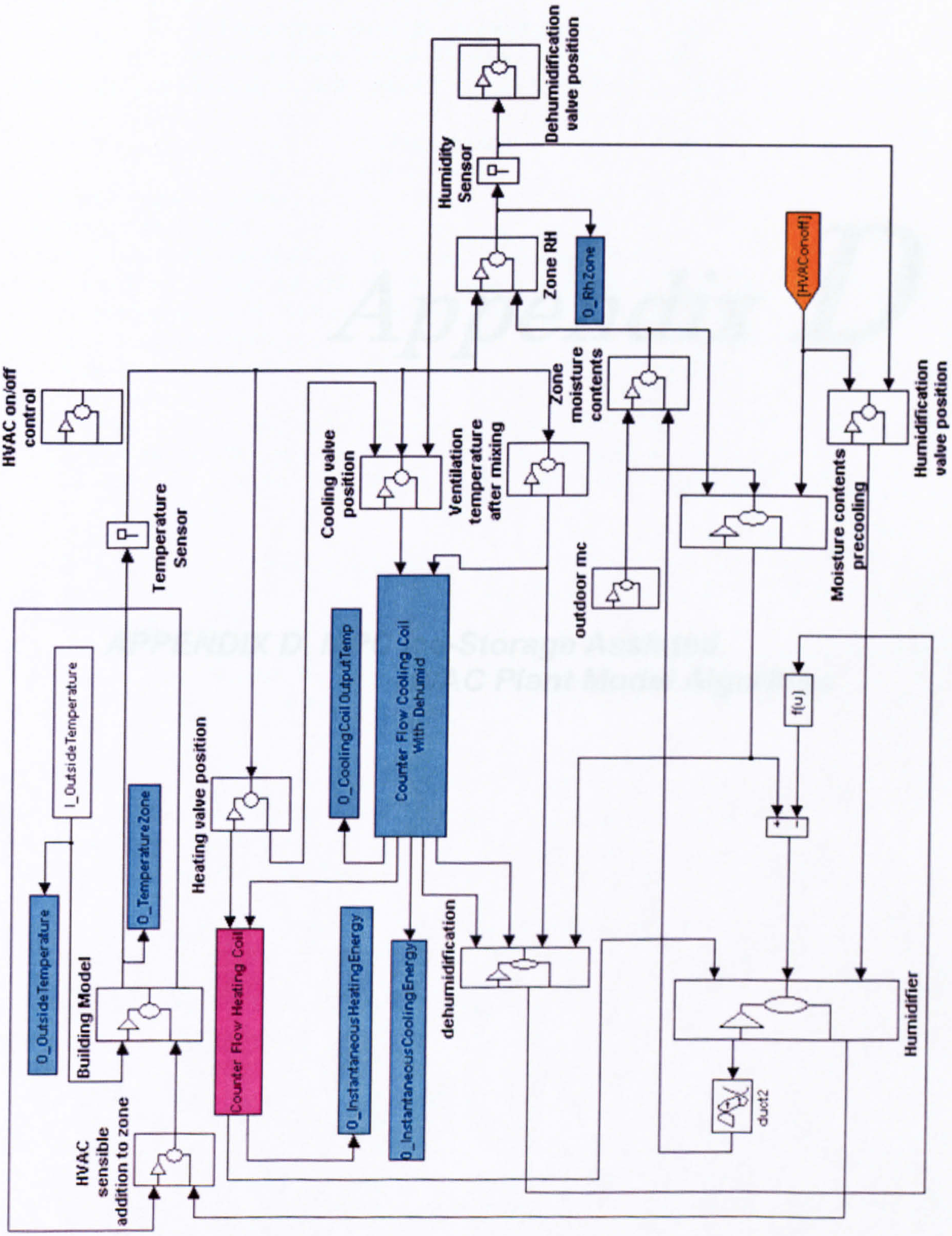

Figure C.1 Simulink building & HVAC model, see Figure 6.9-Block A for details

Appendix D

APPENDIX D MPC Ice-Storage Assisted HVAC Plant Model Algorithm

```
%-----------------------------------------------------------------------------------
%
%            Air Handling Unit Database Generation Code
%            ===========================================
% This program simulates the behaviour of the AHU at variable mixing temperatures
%
%                         MdlRun20.m
%                        ============
% Author: Yehya Al-Hadban
% Date  : 14-10-2004
% Input file: MdlInpVAr20 to load the input variables
% The input file include all the variables such as (weather data, internal
% conditions, building material properties ... etc)
% Output file: MdlRunDat20
% Sample figures of the output is listed within this appendix [Appendix D]
%
% This program runs the model input variables data file and the simulink
% building model. The purpose of doing so is to generate a library of
% vlaues for the mixing temperature Tm that will be needed in another
% code of the model.
%
% In this part of the modelling, we account for the range of chiller outlet
% temperatures (Tcho)=[-8C to 8C] & assume that it is equal to the AHU inlet
% temperature (Tai).
% We also assume that the AHU inlet temperature (Tai)= the mixing temperature(Tm)
% Software used: Matlab version 6.5 Release 13
%-----------------------------------------------------------------------------------


%-----------------------------------------------------------------------------------
% Loop to calculate values of the different variables at different
% mixing temperaures (Tm)
% MdlRun20: Runs simulink building model with AHU [sim20.mdl] 17times
% (Tm)=[-8C to 8C]
% Appendix C, Figure C.1 show's sim20.mdl Simulink diagram
%-----------------------------------------------------------------------------------
clear all;close all;
ott=[];ctt=[];cee=[];ztt=[];cvv=[];na=50;
load ModInpVar20;
for jj=1:17;'17:=8 degC'
Tmean=-9+jj; sim('sim20'); tv=(1:8641)';'Time vector for control loop';

%-----------------------------------------------------------------------------------
%                        Output variables defined
%-----------------------------------------------------------------------------------
ot1=O_OutsideTemperature;
ce1=O_InstantaneousCoolingEnergy;
ct1=O_CoolingCoilOutputTemp;
zt1=O_TemperatureZone;
cv1=O_ValvePositionCooling;
ot2=ot1*1;ct2=ct1*0;ce2=ce1*0;zt2=zt1*0;cv2=cv1*1;
%
```

```
%-----------------------------------------------------------------------------------------%
% Following loops remove spikes in the output in to simplify the control                %
%-----------------------------------------------------------------------------------------%
for ii=na+1:na:8641-(na+1);ot2(ii-na:ii+na)=min(ot1(ii-na:ii+na));end;
ot2(1:na)=ot2(na+1);ot2(end-na:end)=ot2(end-(na+1));
for ii=na+1:na:8641-(na+1);ot2(ii-na:ii+na)=mean(ot1(ii-na:ii+na));end;
ot2(1:na)=ot2(na+1);ot2(end-na:end)=ot2(end-(na+1));
for ii=na+1:na:8641-(na+1);ct2(ii-na:ii+na)=max(ct1(ii-na:ii+na));end;
ct2(1:na)=ct2(na+1);ct2(end-na:end)=ct2(end-(na+1));
for ii=na+1:na:8641-(na+1);ct2(ii-na:ii+na)=mean(ct1(ii-na:ii+na));end;
ct2(1:na)=ct2(na+1);ct2(end-na:end)=ct2(end-(na+1));
for ii=na+1:na:8641-(na+1);ce2(ii-na:ii+na)=min(ce1(ii-na:ii+na));end;
ce2(1:na+100)=ce2(na+100);ce2(end-na:end)=ce2(end-(na+1));
for ii=na+1:na:8641-(na+1);ce2(ii-na:ii+na)=mean(ce1(ii-na:ii+na));end;
ce2(1:na+100)=ce2(na+100);ce2(end-na:end)=ce2(end-(na+1));
for ii=na+1:na:8641-(na+1);zt2(ii-na:ii+na)=min(zt1(ii-na:ii+na));end;
zt2(1:na+100)=zt2(na+100);zt2(end-na:end)=zt2(end-(na+1));
for ii=na+1:na:8641-(na+1);zt2(ii-na:ii+na)=mean(zt1(ii-na:ii+na));end;
zt2(1:na+100)=zt2(na+100);zt2(end-na:end)=zt2(end-(na+1));
%_______________________________________________________________________________________%

ott=ot2;
cee=[cee ce2];
ctt=[ctt ct2];
ztt=[ztt zt2];
cvv=[cvv cv2];
end;'Tmean';
%;ot=ott;ce=cee;ct=ctt;
for kk=1:24;ii=kk*360;
    ot(kk)=ott(ii);
    ce(kk,:)=cee(ii,:);
    ct(kk,:)=ctt(ii,:);
    zt(kk,:)=ztt(ii,:);
    cv(kk,:)=cvv(ii,:);
end;
'save MdlRunDat20 ot ct ce  zt cv';
load MdlRunDat20 ot ce ct zt cv;
%---------------------------------------------------------------------------------------%
%                              Plotting Results                                          %
%---------------------------------------------------------------------------------------%
figure(4);plot(ot);
figure(5);plot(ce);
figure(6);plot(ct);
figure(7);plot(zt);
figure(8);plot(cv);

%------------------------------------------------
% figure(1);plot(ot1);hold on;plot(ot,'r');
% figure(2);plot(ct1);hold on;plot(ct,'r');
% figure(3);plot(ce1);hold on;plot(ce,'r');
%------------------------------------------------

%---------------------------------------------------------------------------------------%
%============================  End of the programme  ============================%
%---------------------------------------------------------------------------------------%
```

```
%------------------------------------------------------------------------------%
%                    Chiller & Ice-Storage Cooling, Charging & Discharging     %
%                    ======================================================    %
% This program represent the chiller and ice-storage with MPC.                 %
%                                                                              %
%                                       SysOp20a.m                             %
%                                       ============                           %
% Author: Yehya Al-Hadban                                                      %
% Date  : 14-10-2004                                                           %
%                                                                              %
% Input file: This program uses look up tables stored as matalab data files, see %
%             Appendices A & B, in order to be able to complete the simulation %
%             Also chiller cooling capacities matlab data file, Table 6.1      %
%                                                                              %
% Input file: MdlRunDat20 to load the database generated from MdlRun20.m       %
% The input file links all the variables such as (weather data, internal       %
% conditions, building material properties ... etc)                            %
%                                                                              %
% Output : Performance tables & figures representing the performance of the    %
% building model & the cooling plant components, such as, the chiller, AHU &   %
% the ice-storage [charging & discharging process].                            %
% The figures in chapter 7 [figures 7.2 to 7.27] are an example of the output  %
% figures generated by this program. In addition, tables 7.1 to 7.9 are also an %
% example what output is given by this program.                                %
% Software used: Matlab version 6.5 Release 13                                 %
%------------------------------------------------------------------------------%

%------------------------------------------------------------------------------%
% mdt:total flow rate m3/s;                                                    %
% mda:flow in AHU;aa=mda/mdt;                                                  %
% mds= flow in ice st;as=portion of flow in ice st/mdt;                        %
%------------------------------------------------------------------------------%
clear all; close all;ee=1e-6;
cp=2.22; gl=0.0631;
mdtC=230*gl;
mdtD=290*gl;dt=1;
TAmx=10;TA=10;UAs=50;

%------------------------------------------------------------------------------%
%                           Loading of chiller data                            %
%------------------------------------------------------------------------------%
CHLfa;qchv=CH0;
load MdlRunDat20 ot ce ct zt cv;
ce=ce/10;

% ot=O_OutsideTemperature;
% ce=O_InstantaneousCoolingEnergy;
% ct=O_CoolingCoilOutputTemp;
% zt=O_TemperatureZone;
% cv=O_ValvePositionCooling;
```

```
%-------------------------------------------------------------------------------------%
 jPlot=0;  '.......................... Start Day Loop  ..........................';
%-------------------------------------------------------------------------------------%
for Hd=1:24;
Tb=ot(Hd);
Tm=0;
qz=ce(Hd,Tm+9);
Ti=zt(Hd,Tm+9);
'Tao=ct(Hd,Tm+9)';
cv1=cv(Hd,Tm+9);

%-------------------------------------------------------------------------------------%
%The Conservation of Energy law ... qs+qch+qz=0 ...  is to be satisifed   %
'......................... Charge, Discharge & Cool Loop  ........................';
%-------------------------------------------------------------------------------------%

Njj=200; IT=0;
adq123=1000;
adq12=1000;
Tcho=6;                                      ' Initial Values';
for jj=1:Njj;close all;                      '.....  Main-loop; to adjust Tchi ....';
adq1231=adq123;adq121=adq12;
if Tm<-8;Tm=-8;end;
if Tm>8;Tm=8;end;
rTm=round(Tm);                                'Tao=ct(Hd,rTm+9)';
Ti=zt(Hd,rTm+9);
qz=ce(Hd,rTm+9);
Tai=Tm;
cv1=cv(Hd,rTm+9);

%-------------------------------------------------------------------------------------%
%                            Chiller calculation                                      %
%-------------------------------------------------------------------------------------%

iL=1+floor((Tb-30)/5);
iH=1+ceil((Tb-30)/5);
qL=qchv(iL,:);
qH=qchv(iH,:);
qm=(qL+qH)/2;
qch=0;Tcho=1000;
[a1 b1]=min(abs(qm-qz));
qchP=-qm(b1);
TchoP=CH(1,b1+1);
dqPt=qchP+qz;
if dqPt<0;qch=qchP;Tcho=TchoP;end;
[a2 b2]=max(abs(qm(1:8)));
qchN=-qm(b2);
TchoN=CH(1,b2+1);
dqNt=qchN+qz;
if dqNt<0;qch=qchN;Tcho=TchoN;end;
if qch==0;qch=qchP;Tcho=TchoP;end;
if Tcho<0;mdt=mdtC;Cmode=1;else mdt=mdtD;Cmode=0;end;
dq12=qch+qz; adq12=abs(dq12);
Tao=Tai+qz/cp/mdt;Tchi=Tao;    aa=1;
```

```
%------------------------------------------------------------------------------------%
%                    Ice storage:  Discharge/Cool mode.                              %
%------------------------------------------------------------------------------------%

Tsi=Tcho;
qsmaxa=UAs*6;                                  '6deg diff';
qs1=(qch+qz);qs1a=abs(qs1);
if qs1a>qsmaxa;qs1a=qsmaxa;end;
qs=0;
if qs1<0&Tsi<0;qs=qs1a;end;
if qs1>0&Tsi>0;qs=-qs1a;end;
r1=(rand-.5)/10;r2=(rand-.5)/10;
Tm=Tsi+qs/mdt/cp;
if Tm<-8;Tm=-8+r1;end;
if Tm>8;Tm=8+r1;end;
Tso=qs/UAs/2-Tsi;
mds=abs((ee+qs))/(ee+abs(Tso-Tsi)*cp);
as=mds/mdt;
dq123=qs+qch+qz; adq123=abs(dq123);

%------------------------------------------------------------------------------------%
%          Loop Controls:    Discharge/Cool mode;                                    %
%------------------------------------------------------------------------------------%

if adq123<20&dq123<=0&jj>10;break;end;
aqch=abs(qch);
dTAH=abs(Tao-Tai);
dTch=abs(Tcho-Tchi);
dTs=abs(Tso-Tsi);
e1=adq1231>adq123;
e2=adq121>adq12;
e3=aqch>700;
e4=dTch>10;
e5=dTs>10;
e=e1|e2|e3|e4|e5;
rT=(rand-.5)/10;
if dq123>0;Tchi=Tchi+.05+rT;end;
if dq123<0;Tchi=Tchi-.05+rT;end;

%------------------------------------------------------------------------------------%
%                          Display variables....                                     %
%------------------------------------------------------------------------------------%

qchh(jj)=qch;
qss(jj)=qs;
Tmm(jj)=Tm;
Tii(jj)=Ti;
Tchoo(jj)=Tcho;
ass(jj)=as;

end;'jj-loop';
if jj==Njj;IT=1;end;                  '  *** End of jj-loop to adjust Tm **********';
```

```
%------------------------------------------------------------------------------------------%
'......................... 3- Plotting Results ........................';
%------------------------------------------------------------------------------------------%

TA=TA+qs ;                           'stored cooling (TA)';
if jPlot==1;
figure(1);hold on;
plot(Tchoo);
plot(Tmm,'--r');
plot(qchh/100,'--');
plot(ass,'g');
plot(qss/100,'--g');
text(2,Tchoo(2),'Tcho,b');
text(4,Tmm(4),'Tm,--r');
text(6,qchh(6)/100,'qch/100,--b');
text(8,qss(8)/100,'qs/100,--g');
xlabel('Tcho(-);qch(--);,as(g);qs(--g);Tm(--r)');
pause(1);hold off;

aval=[jj;Cmode;Hd;Tchi;Tcho;Tsi;Tso;aa;Tai;Tao; TA;qz;qch;qs;as;Tb; Tm; Ti];
astr=['jj    ';'Cmode';'Hd    ';'Tchi  ';'Tcho  ';'Tsi   ';'Tso   ';'aa    ';'Tai   ';
      'Tao   ';'TA    ';'qz    ';'qch   ';'qs    ';'as    ';'Tb    ';'Tm    ';'Ti    '];
avalS=num2str(aval);Astr=[astr avalS];

figure(2);hold on;
plot([0 10],[0 15],'.');
text(1,7,Astr);
if IT==0;text(5,7,'Converged Sol');end;
if IT==1;text(5,7,'No Covergence');end;
pause(1);hold off;
end;'if NjHd';
TAHd(Hd)=(TA);
qchHd(Hd)=(qch);
qsHd(Hd)=(qs);
qzHd(Hd)=qz;
TiHd(Hd)=Ti;
ITHd(Hd)=IT;
cvHd(Hd)=cv1;
TmHd(Hd)=Tm;
asHd(Hd)=as;
end;'jHd';

%------------------------------------------------------------------------------------------%
 ' **************** End Day loop jHd(time of day) ******************';
%------------------------------------------------------------------------------------------%

figure(3);hold on;
plot(ot,'--r');
plot(TiHd,'-g');
plot(TAHd/100,'-m');
plot(qzHd/10,'-r');
plot(qchHd/10,'-');
plot(qsHd/10,'--');
xlabel(' Tb( -r),Ti(- g),TA/100( -m ),qz/10(- -r),qch/10( -),qs/10( - -)');
figure(4);hold on;
```

```
plot(qzHd,'-r');
plot(qchHd,'-');
plot(qsHd,'--')
xlabel('Vals of;  qz(- r), qch(-), qs(- -)');
figure(5);hold on;
plot(TAHd/10,'-m');
plot(qsHd,'--');
plot(ITHd*TAmx/10,'.m');
xlabel('Ice Storage State TA(kW/10,m), qs(--) and IT(. m)');
figure(6);
plot(TiHd,'-g');
xlabel('Ti(g)');
figure(7);hold on;
plot(cvHd,'m');
plot(TmHd);
plot(asHd,'. m');
xlabel('Tm(degC,bl) cooling v opening(m) and st v opening(. m)');

%-----------------------------------------------------------------------------------%
%===========================  End of the programme  ==============================%
%-----------------------------------------------------------------------------------%
```

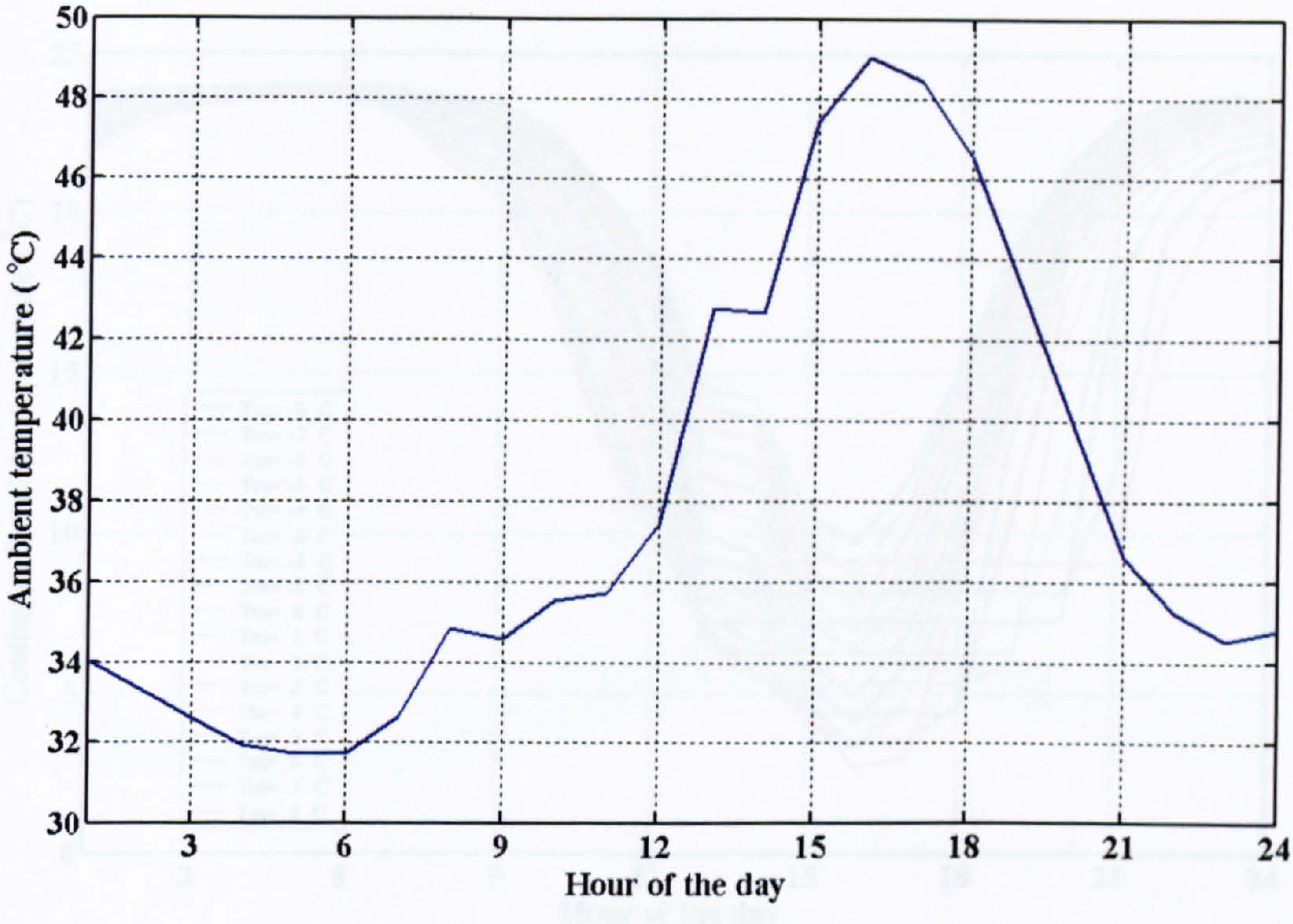

Figure D.1 Ambient temperature for a selected day (°C)

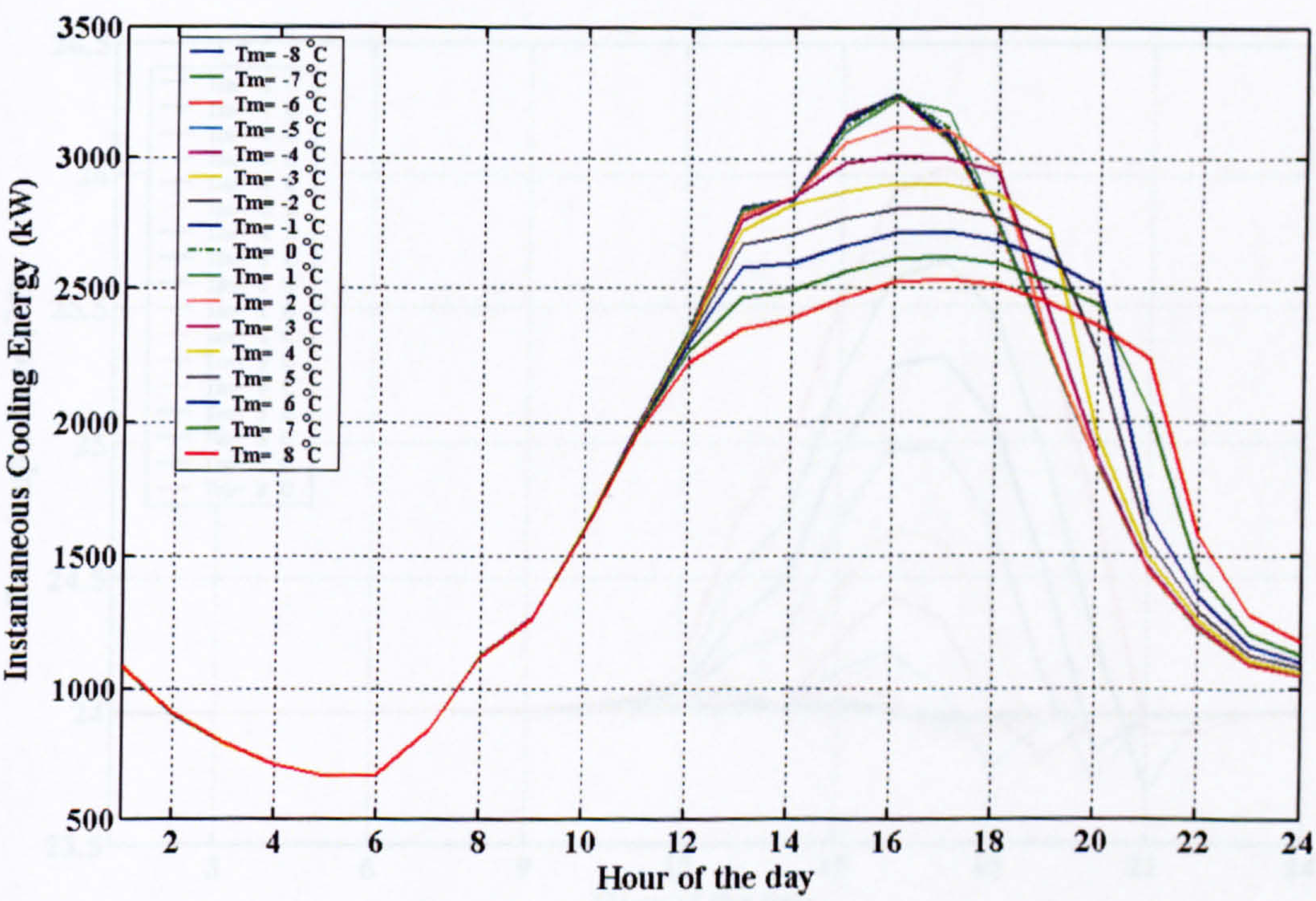

Figure D.2 Chiller output in relation to the cooling load at different chiller outlet temperatures (Tcho)

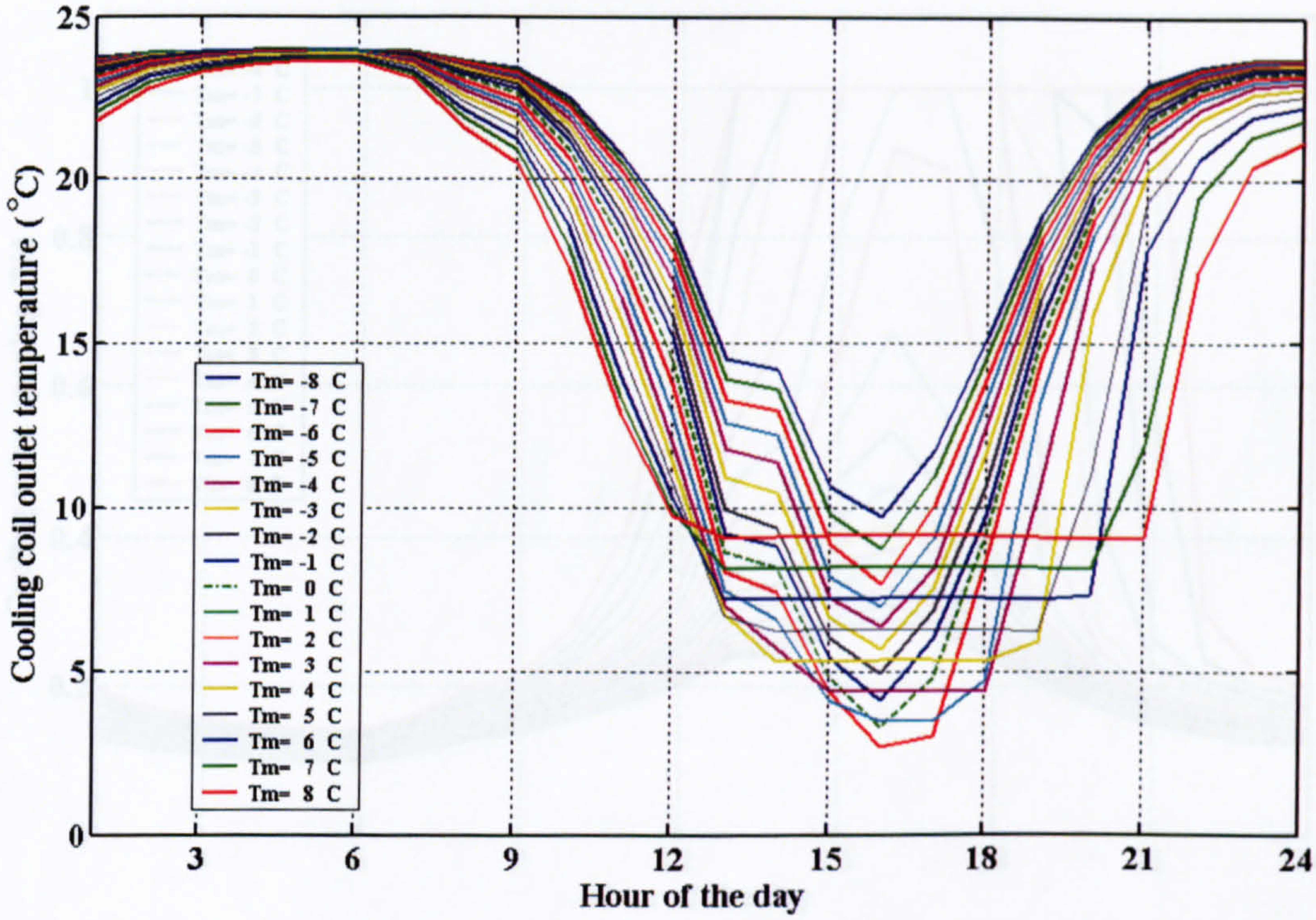

Figure D.3 AHU outlet temperature (Tao) at different chiller outlet temperature (Tcho)

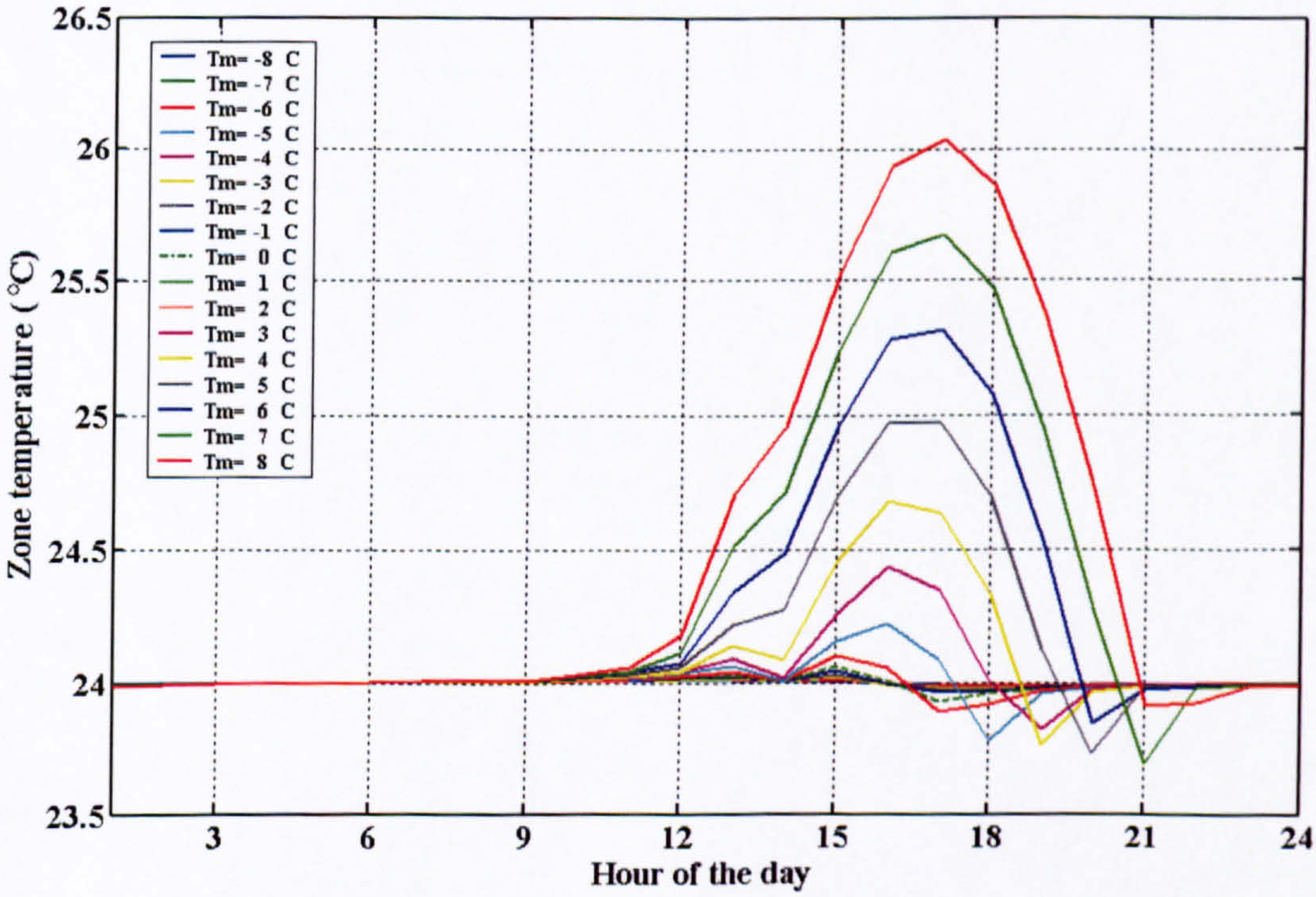

Figure D.4 Zone temperature at different chiller outlet temperature (Tcho)

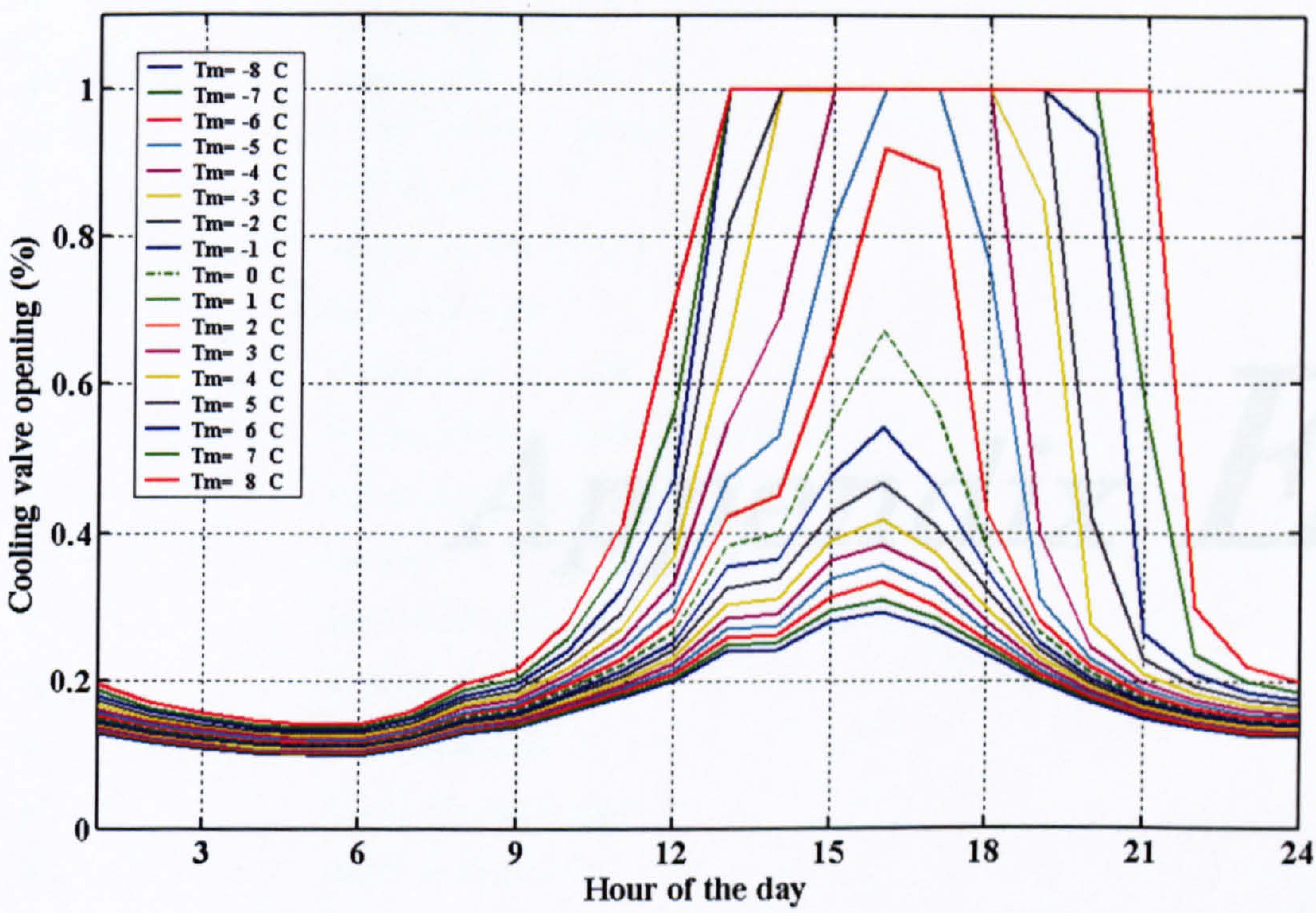

Figure D.5 Cooling valve opening at different chiller outlet temperature (Tcho)

Appendix E

APPENDIX E Nomenclature

α	Thermal diffusivity
αa	Control valve – System
αs	Control valve – ice storage
β	surface slope (^{o})
γ	surface azimuth angle (^{o})
δ	declination angle (^{o})
$\Delta\tau$	simulation time step (seconds)
$\Delta\xi$	building partition division thickness (m)
ε	Heat transfer effectiveness
ϕ	latitude (^{o})
θ	angle of incidence (^{o})
θ_ζ	zenith angle (^{o})
θ_τ	transmission angle (^{o})
ρ	density of material (kg/m^3)
$\rho_{\rho\iota\alpha}$	density of air (kg/m^3)
ρ_γ	reflectance of the ground (dimensionless)
$\tau(\theta)$	glass layer transmittance at angle of incidence θ (dimensionless)
τ_o	glass layer normal transmittance (dimensionless)
$\tau_{\alpha\rho\alpha\pi}$	transmittance parallel to plane of incidence (dimensionless)
$\tau_{\pi\rho\varepsilon\pi}$	transmittance perpendicular to plane of incidence (dimensionless)
ω	hour angle (^{o})
A	area of surface i (m^2)
$b(\theta)$	attenuation factor at angle of incidence θ (dimensionless)
Bi	Biot Number (dimensionless)
b_o	attenuation factor normal angle of incidence(dimensionless)
$c(\theta)$	ratio of the cosine of the transmission angle to the cosine of the angle of incidence (dimensionless)
C_{DC}	Chiller day capacity
C_{IMC}	Chiller ice making capacity
C_{min}	Chiller tonnage
c_p	specific heat capacity (J/kgK)
c_{pair}	specific heat capacity air (J/kgK, J/m^{3}K)
d	thickness of glass layer (m)
h	day hours

F_o	Fourier Number (dimensionless)
H	surface height (m)
h_i	internal surface convective heat transfer coefficient (W/m^2K)
h_o	external surface convective heat transfer coefficient (W/m^2K)
h_{ro}	external surface radiative heat transfer coefficient (W/m^2K)
$I_{diffusemean}$	mean surface diffuse irradiance (including scattered) (W/m^2)
$I_{Hdiffuse}$	diffuse radiation on a horizontal surface (W/m^2)
$I_{Hdirect}$	direct radiation on a horizontal surface (W/m^2)
I_{Htotal}	total radiation on a horizontal surface (W/m^2)
$I_{Idiffuse}$	diffuse radiation on an inclined surface (W/m^2)
$I_{Idirect}$	direct radiation on an inclined surface (W/m^2)
I_{Igref}	ground reflected radiation on an inclined surface (W/m^2)
I_{Itotal}	total radiation on an inclined surface (W/m^2)
h_{IM}	ice-making hours
k	thermal conductivity (W/mK)
n	refractive index (n = 1.52 for glass)
n_d	day number (Jan 1^{st} = 1, Dec 31^{st} = 365)
q_{ch}	Chiller load
q_r	Radiant heat transfer to internal surface (W/m^2)
q_s	Ice-storage laod
q_z	Load from zone
R_b	The ratio of direct radiation incident on a tilted surface to that on a horizontal surface (dimensionless)
C_s	The required storage capacity
T_{air}	Air dry bulb temperature (°C)
T_{chi}	Chiller inlet temperature
T_{cho}	Chiller outlet temperature
T_{ao}	AHU outlet temperature
T_{ai}	AHU intlet temperature
T_{so}	Storage outlet temperature
T_{si}	Storage inlet temperature
T_m	Mixing temperature
T_b	Ambient temperature
$C_{R,tot}$	Total cooling requirement

T_i	Internal air temperature (K)
T_o	External air temperature (K)
t_{para}	Surface transmittance parallel to plane of incidence (dimensionless)
t_{perp}	Surface transmittance perpendicular to plane of incidence (dimensionless)
x	Building partition thickness (m)
x_c	Extinction coefficient for a material (m^{-1})